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Water desalination systems powered by renewable energy sources: Review

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ABSTRACT

Water and energy are two of the most important topics on the international environment and development agenda. The social and economic health of the modern world depends on sustainable supply of both energy and water. Many areas worldwide that suffer from fresh water shortage are increasingly dependent on desalination as a highly reliable and non-conventional source of fresh water. So, desalination market has greatly expanded in recent decades and expected to continue in the coming years. The integration of renewable energy resources in desalination and water purification is becoming increasingly attractive. This is justified by the fact that areas of fresh water shortages have plenty of solar energy and these technologies have low operating and maintenance costs.

The present paper presents a review for the work that has been achieved during the recent years in the field of desalination by renewable energies, with emphasis on technologies and economics. The review also includes water sources, demand and availability of potable water and purification methods. A comparative study between different renewable energy technologies powered desalination systems as well as performance and economics have been done. Finally, some general guidelines are given for selection of desalination and renewable energy systems and the parameters that need to be considered.

Contents

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Nomenclature

AC	alternative current
ADS	autonomous desalination system
BOE	barrel of oil equivalent
BW	brackish water
BWRO	brackish water reverse osmosis
CdS	compounds of cadmium sulphide
CLFR	compact linear Fresnel reflector
CPC	compound parabolic collectors
CTC	cylindrical trough collector
CPV	concentrating photovoltaic
CR	concentration ratio is defined as the aperture area divided by the receiver/absorber area of the collector
Cu_2S	cuprous sulphide
DC	direct current
DOD	maximum depth of discharge (for batteries)
DST	decision support tool software
E_L	load energy
ED	electro-dialysis
ER-RO	energy recovery reverse osmosis systems
ETC	evacuated tube collector
FPC	flat plate collector
GaAs	gallium arsenide
GCC	gulf cooperation council
GOR	gain output ratio—the [illegible] fresh water output (distillate) to steam.
GW_p	gega watt (as peak load)
HFC	heliostat field collector
kW	kilowatt
kWh	kilowatt-hour
KJC	operating com[illegible] of Kram[illegible] Junction, California
RO	reve[illegible]osis [illegible]
LFR	li[illegible] Fresnel reflec[illegible]
LTV	[illegible]g tube vertical (ME[illegible] plant)
ME	[illegible]ltipl[illegible]
MEB	m[illegible]e-effect boiling
MEE	mul[illegible] effect evaporation
MES	multip[illegible]ect stack
MF	micro-filtration
MSF	multi-stage flash
MW	megawatt
NF	nanofiltration
NREL5	US National Renewable Energy Laboratory
O&M	operation and maintenance
PPM	parts per million (milligram per liter)
PR	performance ratio
PTC	parabolic trough collector
(PV-RO)	photovoltaic-powered reverse osmosis system
PV/RO	photovoltaic and RO combination
RE/RO	renewable energy and re[illegible] osmosis [illegible]mbinations
RES	renewable energy sources
RO	reverse osmo[illegible]
SCA	solar collecto[illegible]
SEGS	solar en[illegible]y gen[illegible]ng syste[illegible]
Si	silic[illegible]
SW	se[illegible]
SW-RO	s[illegible]water [illegible]erse osmosis
SWCC	Saline Wat[illegible]nversion Corporation
TD[illegible]	[illegible]otal dissolved [illegible]ids contained in water
[illegible]	ultrafiltration
[illegible]	volt
[illegible]	vapo[illegible]mpression which can be thermal (TVC) or mec[illegible]ic (MVC)
W	[illegible]
WIND/RO	wind energy and reverse osmosis combinations

Greek symbol

η	efficiency

Subscripts

e	effective
p	peak

1. Introduction

1.1. Natural water resources

Water is one of the most abundant resources on Earth, covering three-fourths of the planet's surface. About 97% of the Earth's water is salt water in the oceans and 3% is fresh water contained in the poles (in the form of ice), ground water, lakes and rivers, which supply most of human and animal needs. Nearly, 70% from this tiny 3% of the world's fresh water is frozen in glaciers, permanent snow cover, ice and permafrost. Thirty percent of all fresh water is underground, most of it in deep, hard-to-reach aquifers. Lakes and rivers together contain just a little more than 0.25% of all fresh water; lakes contain most of it [1,2].

1.2. Water demand and consumption

Man has been dependent on rivers, lakes and underground water reservoirs for fresh water requirements in domestic life, agriculture and industry. About 70% of total water consumption is used by agriculture, 20% is used by the industry and only 10% of the water consumed worldwide is used for household needs [1].

However, rapid industrial growth and the worldwide population explosion have resulted in a large escalation of demand for fresh water, both for the household needs and for crops to produce

adequate quantities of food. Added to this is the problem of pollution of rivers and lakes by industrial wastes and the large amounts of sewage discharged. In total, water demand doubles every 20 years, so the water emergency situation is certainly very alarming [1,2].

1.3. The need for desalination

The only nearly inexhaustible sources of water are the oceans. Their main drawback, however, is their high salinity. Therefore, it would be attractive to tackle the water-shortage problem with desalination of this water.

Desalinize in general means to remove salt from seawater or generally saline water. According to World Health Organization (WHO), the permissible limit of salinity in water is 500 parts per million (ppm) and for special cases up to 1000 ppm, while most of the water available on Earth has salinity up to 10,000 ppm, and seawater normally has salinity in the range of 35,000–45,000 ppm in the form of total dissolved salts [1,2].

Excess water salinity causes the problem of taste, stomach problems and laxative effects. The purpose of a desalination system is to clean or purify brackish water or seawater and supply water with total dissolved solids within the permissible limit of 500 ppm or less. This is accomplished by several desalination methods that will be analyzed in this paper.

1.4. Desalination and energy

In general, energy is as important as water for the development of good standards of life because it is the force that puts in operation all human activities. Desalination processes require significant quantities of energy to achieve separation of salts from seawater. The dramatic increase of desalinated water supply will create a series of problems, the most significant of which are those related to energy consumption and environmental pollution caused by the use of fossil fuels. Renewable energy systems produce energy from sources that are freely available in nature. Their main characteristic is that they are friendly to the environment, i.e. they do not produce harmful effluents. Production of fresh water using desalination technologies driven by renewable energy systems is thought to be a viable solution to the water scarcity at remote areas characterized by lack of potable water and conventional energy sources like heat and electricity grid. Worldwide, several renewable energy desalination pilot plants have been installed and the majority has been successfully operated for a number of years. Virtually, all of them are custom designed for specific locations and utilize solar, wind or geothermal energy to produce fresh water. Operational data and experience from these plants can be utilized to achieve higher reliability and cost minimization. Although renewable energy powered desalination systems cannot compete with conventional systems in terms of the cost of water produced, they are applicable in certain areas and are likely to become more widely feasible solutions in the near future.

1.5. Desalination market

Many areas worldwide that suffer from fresh water shortage are increasingly dependent on desalination, as a highly reliable and non-conventional source of fresh water. Desalination market has greatly expanded in recent decades and they are expected to continue expanding in the coming years.

Seawater desalination is being applied at 58% of installed capacity worldwide, followed by brackish water desalination accounting for 23% of installed capacity [1,2]. Fig. 1 outlines the global desalting capacity ranked according to feed water sources.

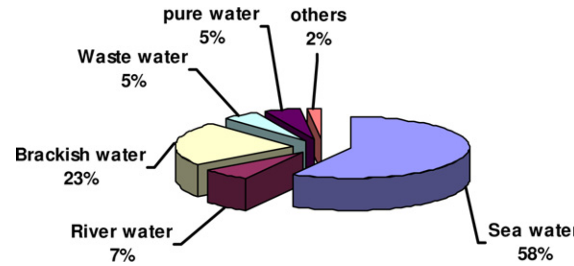


Fig. 1. Global installed desalination capacity by feed-water sources [1].

1.6. Objectives

This paper presents a description of the various methods used for water desalination. Special attention is given to the use of renewable energy systems in desalination. Among the various renewable energy systems, the ones that have been used, or can be used, for desalination are reviewed. These include solar thermal collectors, solar ponds, photovoltaic, wind turbines and geothermal energy.

2. Water desalination techniques

Water desalination can be achieved by different techniques that can be classified under two categories: called as thermal and membrane processes. In the thermal processes (phase-change), the distillation of seawater is achieved by utilizing a thermal energy source. The thermal energy may be obtained from a conventional fossil-fuel source, nuclear energy or from a non-conventional solar energy source or geothermal energy. In the membrane processes, electricity is used either for driving high-pressure pumps or for ionization of salts contained in the seawater.

Commercial desalination processes based on thermal energy are multi-stage flash (MSF) distillation, multiple effect boiling (MEB) and vapor compression (VC), which could be thermal (TVC) or mechanical (MVC). MSF and MEB processes consist of a set of stages at successively decreasing temperature and pressure. MSF process is based on the generation of vapor from seawater or brine due to a sudden pressure reduction when seawater enters an evacuated chamber. The process is repeated stage by stage at successively decreasing pressure. This process requires an external steam supply, normally at a temperature around 100 °C. The maximum temperature is limited by the salt concentration to avoid scaling and this maximum limits the performance of the process. On MEB, vapors are generated due to the absorption of thermal energy by the seawater. The steam generated in one stage or effect is able to heat the salt solution in the next stage because the next stage is at a lower temperature and pressure. The performance of the MEB and MSF processes is proportional to the number of stages or effects. MEB plants normally use an external steam supply at a temperature of about 70 °C. On TVC and MVC, after initial vapor is generated from the saline solution, this vapor is thermally or mechanically compressed to generate additional production.

Not only distillation processes involve phase change, but also freezing and humidification/dehumidification processes. The conversion of saline water to fresh water by freezing has always existed in nature and has been known to man for thousands of years. In desalination of water by freezing, fresh water is removed and leave behind concentrated brine. It is a separation process related to the solid–liquid phase change phenomenon. When the temperature of saline water is reduced to its freezing point, which is a function of salinity, ice crystals of pure water are formed within the salt solution. These ice crystals can be mechanically separated from the concentrated solution, washed and re-melted to obtain pure water.

Table 1
Desalination processes [2].

I-Phase-change processes:
I-1. Multi-stage flash (MSF)
I-2. Multiple effect boiling (MEB)
I-3. Vapor compression (VC)
I-4. Freezing
I-5. Humidification/dehumidification
I-6. Solar stills:
a. Conventional stills
b. Special stills
c. Cascaded type solar stills
d. Wick-type stills
e. Multiple-wick-type stills
II-Membrane processes
II-1. Reverse osmosis (RO):
a. RO without energy recovery
b. RO with energy recovery (ER-RO)
II-2. Electro-dialysis (ED)
II-3. Nanofiltration

Therefore, the basic energy input for this method is for the refrigeration system [2]. Humidification/dehumidification method also uses a refrigeration system but the principle of operation is different. The humidification/dehumidification process is based on the fact that air can be mixed with large quantities of water vapor. Additionally, the vapor carrying capability of air increases with temperature [2]. In this process, seawater is added into an air stream to increase its humidity. Then this humid air is directed to a cool coil on the surface of which water vapor contained in the air is condensed and collected as fresh water. These processes, however, exhibit some technical problems which limit their industrial development. As these technologies have not yet industrially matured, they are [illegible] included in this paper.

The other category of industrial desalination processes does not involve phase change but membranes. These are the reverse osmosis (RO) and electro-dialysis (ED). The first one requires electricity or shaft power to drive the pump that increases the pressure of the saline solution to that required. The required pressure depends on the salt concentration of the resource of saline [illegible] normally around 70 bar for seawater desalination.

ED also requires electricity for the ionization of water which is cleaned by using suitable membranes located at the two oppositively charged electrodes. Both of them, RO and ED are used for brackish water desalination, but only RO competes with distillation processes in seawater desalination. The dominant processes are MSF and RO, which account for [illegible] and 42% of worldwide capacity, respectively [1,2]. The MSF process represents more than 93% of the thermal process production, while RO process represents more than 88% of membrane processes production [2]. All the above processes are listed in Table 1 and described in more detail in the present section [1–8].

Solar energy can [illegible] seawater desalination either by producing thermal energy required to drive the phase change processes or by producing electricity required to drive the membrane processes. Solar desalination systems are thus classified into two categories, i.e. direct and indirect collection systems. As their name implies, direct collection systems use solar energy to produce distillate directly in the solar collector, whereas in indirect collection systems, two sub-systems are employed (one for solar energy collection and one for desalination). Conventional desalination systems are similar to solar systems since the same type of equipment is applied. The prime difference is that in the former, either a conventional boiler is used to provide the required heat or mains electricity is used to provide the required electric power, whereas in the latter, solar energy is applied. The most promising and applicable renewable energy systems (RES) desalination combinations are shown in Table 2.

Table 2
The most promising and applicable RES–desalination combinations [2].

RES technology	Feed water salinity	Desalination technology
Solar thermal	Seawater	Multiple effect boiling (MEB)
	Seawater	Multi-stage flash (MSF)
Photovoltaic	Seawater	Reverse osmosis (RO)
	Brackish water	Reverse osmosis (RO)
	Brackish water	Electrodialysis (ED)
Wind energy	Seawater	Reverse osmosis (RO)
	Brackish water	Reverse osmosis (RO)
	Seawater	Mechanical vapor compression (MVC)
Geothermal	Seawater	Multiple effect boiling (MEB)

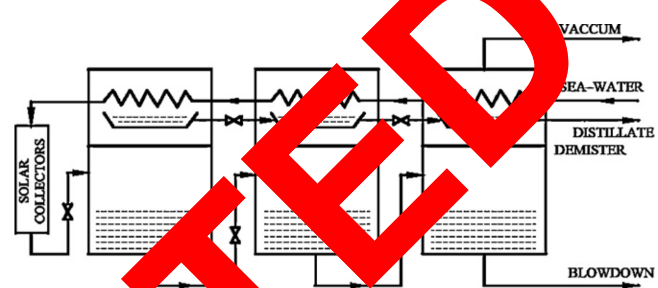


Fig. 2. Principle of operation of the multi-stage flash (MSF) system [2].

The operating principle of thermal processes entails reusing the latent heat of evaporation to preheat the feed while at the same time condensing steam to produce fresh water. The energy requirements of these systems are traditionally defined in terms of units of distillate produced per unit mass (kg) of steam or per 2326 kJ heat input, which corresponds to the latent heat of vaporization at 73 °C. The dimensional ratio in kg/2326 kJ is known as the performance ratio, PR [2]. The operating principle of membrane processes leads to the direct production of electricity from solar or wind energy, which is used to drive the plant. Energy consumption is usually expressed in kWhe/m^3 [2].

2.1. Thermal processes (phase change)

The thermal processes can be subdivided into the following processes.

2.1.1. Multistage flash evaporation (MSF)

The MSF process is composed of a series of elements called stages. In each stage, condensing steam is used to preheat the seawater feed. By fractionating the overall temperature differential between the warm source and seawater into a large number of stages, the system approaches ideal total latent heat recovery. Operation of this system requires pressure gradients in the plant. The principle of operation is shown in Fig. 2 Current commercial installations are designed with 10–30 stages (2 °C temperature drop per stage).

A practical cycle representing the MSF process is shown in Fig. 3. The system is divided into heat-recovery and heat-rejection

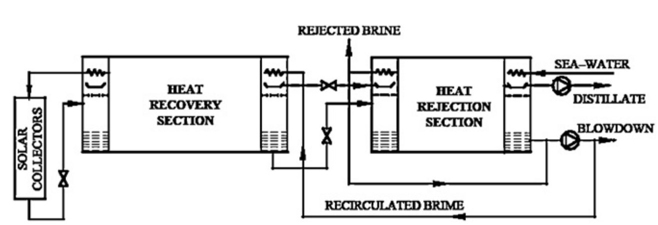


Fig. 3. A multi-stage flash (MSF) process plant [2].

sections. Seawater is fed through the heat-rejection section, which rejects thermal energy from the plant and discharges the product and brine at the lowest possible temperature. The feed is then mixed with a large mass of water, which is re-circulated around the plant. This water then passes through a series of heat exchangers to raise its temperature. The water next enters the solar collector array or a conventional brine heater to raise its temperature to nearly the saturation temperature at the maximum system pressure. The water then enters the first stage through an orifice and in so doing has its pressure reduced. Since, the water was at the saturation temperature for a higher pressure, it becomes superheated and flashes into steam. The vapor produced passes through a wire mesh (demister) to remove any entrained brine droplets and thence into the heat exchanger, where it is condensed and drips into a distillate tray. This process is repeated through the plant as both brine and distillate streams flash as they enter subsequent stages, which are at successively lower pressures.

In MSF, the number of stages is not tied rigidly to the PR required from the plant. In practice, the minimum must be slightly greater than the PR, while the maximum is imposed by the boiling-point elevation. The minimum inter-stage temperature drop must exceed the boiling-point elevation for flashing to occur at a finite rate. This is advantageous because as the number of stages is increased, the terminal temperature difference over the heat exchangers increases and hence less heat transfer area is required with obvious savings in plant capital cost [2].

MSF is the most widely used desalination process in terms of capacity. This is due to the simplicity of the process, performance characteristics and scale control [2]. A disadvantage of MSF is that precise pressure levels are required in the different stages and therefore some transient time is required to establish the n l running operation of the plant. This feature makes the MS tively unsuitable for solar energy applications unless a storage k is used for thermal buffering [2].

Moustafa et al. [8] reported on the performan 0 m^3/d solar MSF desalination system tested in Kuwa he em con sisted of a 220 m^2 parabolic trough collect 7000 l thermal storage and a 12-stage MSF desalination syst Th age system was used to level off the rmal y supply and allowed the production of fresh wat continue g periods of low radiation and night-time. Th of the syste reported to be over 10 times the outpu of sol lls for the same solar collection area.

2.1.2. Multiple effect b ng (M

The MEB process s n i g. 4 is also composed of a number of elements, which are cal ects. Th am from one effect is used as heating fl other ct, h while condensing, causes evaporati a pa f the sa tion. The produced steam goes throug follo g effect, where, while condensing, it makes some of t th porate and so on. For this procedure

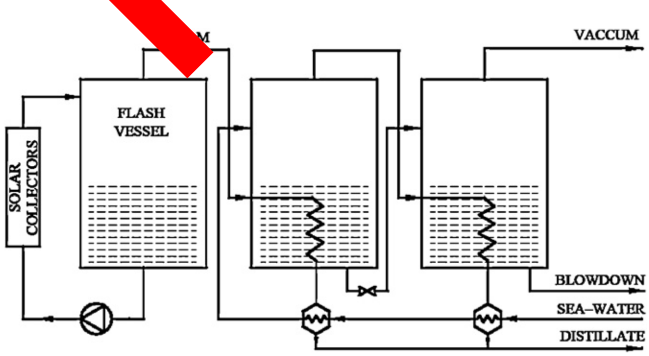


Fig. 4. Principle of operation of a multiple-effect boiling (MEB) system [2].

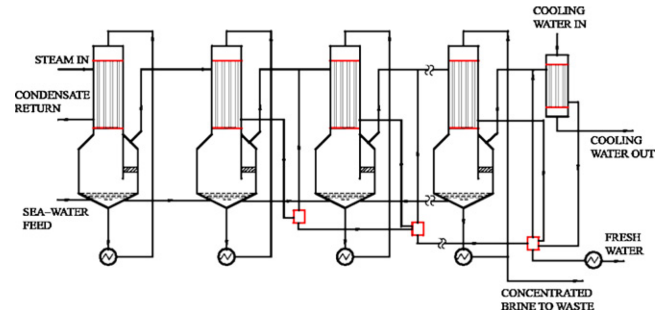


Fig. 5. Long tube vertical (LTV) [2].

to be possible, the heated eff t mu kept at a essure lower than that of the effect from h the h g stea originates. The solutions condensed by a ects are use heat the feed [5]. In this process, vapor roduc y flashi and by boiling, but the majority of the dist i oduced y boiling. Unlike an MSF plant, the MEB p ss us operat s a once through system without a larg ass of brin ci ting around the plant. This design red pumping r ements and scaling tendencies [1,2].

As with the MSF p the incoming brine in the MEB process pa ugh a series o aters but after passing through the last ese, instead of entering the brine heater, the feed enters the effect, wh the heating steam raises its temperature to the s ration tem ature for the effect pressure further amounts of ste either m a solar collector system or from a conventional boile d to produce evaporation in this effect. The vapor then goes, in part, to heat the incoming feed and, in part, to provide t supply for the second effect, which is at a lower pressure and receives its feed from the brine of the first effect. This process is repeated all the way through (down) the plant. The distillate also passes down the plant. Both the brine and distillate flash as they travel down the plant due to progressive reduction in pressure [2].

There are many possible variations of MEB plants, depending on the combinations of heat-transfer configurations and flow-sheet arrangements used. Early plants were of the submerged tube design and used only two to three effects. In modern systems, the problem of low evaporation rate has been resolved by making use of the thin film designs with the feed liquid distributed on the heating surface in the form of a thin film instead of a deep pool of water. Such plants may have vertical or horizontal tubes. The vertical tube designs are of two types: climbing film, natural and forced circulation type or long tube, vertical (LTV), straight falling film type. In the LTV plants shown in Fig. 5, the brine boils inside the tubes and the steam condenses outside. In the horizontal tube, falling-film design, the steam condenses inside the tube with the brine evaporating on the outside.

With multiple evaporation, the underlying principle is to make use of the available energy of the leaving streams of a single-evaporation process to produce more distillate.

Another type of MEB evaporator is the multiple effect stack type (MEB-MES). This is the most appropriate type for solar energy application. It has a number of advantages, the most important of which is its stable operation between virtually 0 and 100% output even when sudden changes are made and its ability to follow a varying steam supply without upset [2]. In Fig. 6, a four-effect MES evaporator is shown. Seawater is sprayed into the top of the evaporator and descends as a thin film over the horizontally arranged tube bundle in each effect. In the top (hottest) effect, steam from a steam boiler or from a solar collector system condenses inside the tubes. Because of the low pressure created in the plant by the vent-ejector system, the thin seawater film boils simultaneously on the outside of the

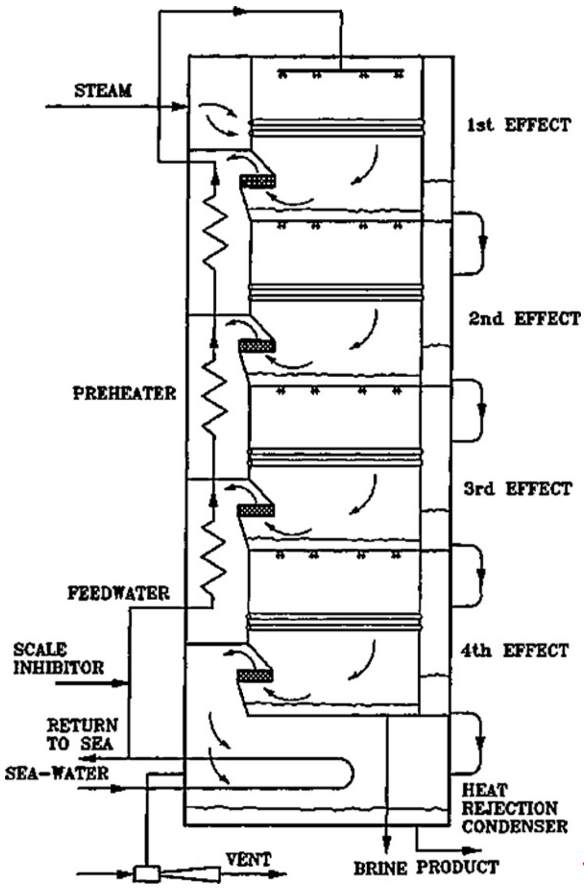


Fig. 6. Schematic of the MEB process with the multi effect stack type evapora[illegible] (MEB-MES) [2].

tubes, thus creating new vapor at a lower te[illegible]rature [illegible]an the condensing steam.

The seawater falling to the floor of th[illegible]rst e[illegible] cooled by flashing through nozzles into the seco[illegible]ffect, which [illegible]t a lower pressure. The vapor made in the firs[illegible]ducted into [illegible]inside of the tubes in the second effect, w[illegible]re it c[illegible]nses to form part of the product. Furthermore, the [illegible]ndensing w[illegible]vapor causes the external cooler seawater fi[illegible]o boil at the redu[illegible] pressure.

The evaporation–co[illegible]sation [illegible]cess is repeated from effect to effect in the plant, c[illegible]g a[illegible]most equal amount of product inside the tubes of each e[illegible] he va[illegible]made in the last effect is condensed o[illegible]tside [illegible]tub[illegible]ndle cooled by raw seawater. Most [illegible]e w[illegible]er sea[illegible]s then returned to the sea, but a sma[illegible]rt is [illegible]d as feed-water to the plant. After being treated wit[illegible]d [illegible]e forming compounds, the feed-water passes [illegible]e stack through a series of pre-heaters that use a little of the [illegible]or from each effect to raise its temperature gradually, before it [illegible]rayed into the top of the plant. The water produced from each effect is flashed in a cascade down the plant so that it can be withdrawn in a cool condition at the bottom of the stack. The concentrated brine is also withdrawn at the bottom of the stack. The MES process is completely stable in operation and automatically adjusts to changing steam conditions even if they are suddenly applied, so it is suitable for load-following applications. It is a once-through process that minimizes the risk of scale formation without incurring a large chemical scale dosing cost. The typical product purity is less than 5 ppm TDS and does not deteriorate as the plant ages. Therefore, the MEB process with the MES type evaporator (MEB-MES) appears to be the most suitable for use with solar energy.

Unlike the MSF plant, the performance ratio for an MEB plant is more rigidly linked to and cannot exceed a limit set by the number of effects in the plant. For instance, a plant with 13 effects might typically have a PR of 10. However, an MSF plant with a PR of 10 could have 13–35 stages depending on the design. MSF plants have a maximum PR of approximately 13. Normally, the figure is between 6 and 10. MEB plants commonly have performance ratios as high as 12–14 [2]. The main difference between this process and the MSF is that the steam of each effect just travels to the following effect, where it is immediately used for preheating the feed. This process requires more complicated circuit equipment than the MSF; on the other hand, it has the advantage that is suitable for solar energy utilization because the levels of operating t[illegible]e and pressure equilibrium are less critical [2].

A 14-effect MEB plant with a n[illegible]al output [illegible] m^3/h and coupled with 2672 m^2 parabolic troug[illegible]llectors (P[illegible]) has been presented by Kalogirou [2]. The [illegible]tem is [illegible]led at [illegible] plataforma solar de Almeria in Southe[illegible]pain. It also [illegible]tes a 155 m^3 thermo-cline thermal sto[illegible] tank. [illegible] circulat[illegible]uid through the solar collectors is a synthe[illegible] h[illegible]-transfe[illegible] fluid (3M Santotherm 55). The performan[illegible]tio (P[illegible]tained [illegible]he system varies from 9.3 to 10.7, depe[illegible]ng on the [illegible]liti[illegible] of the evaporator tube-bundle surfac[illegible] [illegible]uthors esti[illegible]d that the efficiency of the system can b[illegible] incre[illegible] considerably by recovering the energy wasted when part of th[illegible]oling water in the final condenser is reject[illegible]rgy recovery is [illegible]formed with a double-effect absorption [illegible]at pump.

[illegible] Nashar [8] [illegible]es details of a MEB-MES system powered with 18[illegible] m^2 evacuate[illegible]ube collectors. The system is installed in Abu Dhab[illegible]ited A[illegible] Emirates. A computer program was developed for the [illegible]ion of the operating parameters of the plant that [illegible]ct its performance, i.e. the collector area in service, the high te[illegible]re collector set point and the heating water flow rate. [illegible]e maximum daily distillate production corresponding to the optimum operating conditions was found to be 120 m^3/day, which can be obtained for 8 months of the year.

2.1.3. Vapour compression (VC)

In a VC plant, heat recovery is based on raising the pressure of the steam from a stage by means of a compressor, see Fig. 7. The condensation temperature is thus increased and the steam can be used to provide energy to the same stage it came from or to other stages [1–7]. As in a conventional MEB system, the vapor produced in the first effect is used as the heat input to the second effect, which is at a lower pressure. The vapor produced in the last effect

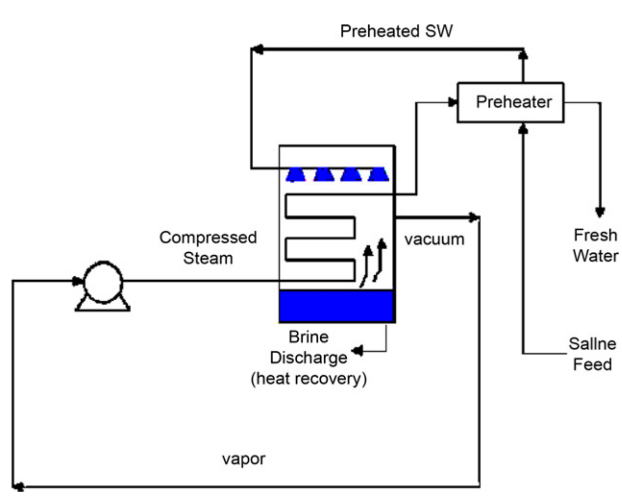


Fig. 7. Schematic diagram of a single stage mechanical vapor compression desalination process [1].

is then passed to the vapor compressor, where it is compressed and its saturation temperature is raised before it is returned to the first effect. The compressor represents the major energy input to the system and since the latent heat is effectively recycled around the plant, the process has the potential for delivering high PR [2].

Parametric cost estimates and process designs have been carried out and show that this type of plant is not particularly convenient, unless it is combined with an MEB system.

Furthermore, it appears that the mechanical energy requirements have to be provided with a primary drive such as a diesel engine, and cooling the radiator of such an engine provides more than enough heat for the thermal requirements of the process, making the solar collector system redundant [2]. Therefore, the VC system can be used in conjunction with an MEB system and operated at periods of low solar radiation or overnight.

Vapor compression systems are subdivided into two main categories: mechanical vapor compression (MVC) and thermal vapor compression (TVC) systems. The mechanical vapor compression systems employ a mechanical compressor to compress the vapor, whereas the thermal one utilize a steam jet compressor. The main problems associated with the MVC process are [2]:

(i) Vapor containing brine is carried over into the compressor and leads to corrosion of the compressor blades.
(ii) There are plant-size limitations because of limited compressor capacities.

Thermal vapor systems are designed for projects, where steam is available. The required pressure is between 2 and 10 bar and due to the relatively high cost of the steam, a large number of evaporative-condenser heat recovery effects are normally justified.

Thermal performance and energy analysis of a TVC syst[em] is presented by Hamed et al. [9] and they found that:

(1) Operational data of a four-effect, low te[mperature] therm[al] vapor compression desalination plant [rev]ealed [tha]t performance ratios of 6.5–6.8 can be attained. [illegible] rat[illegible] twice those of a conventional four[-eff]ect [illegible] desalination plant.
(2) The performance ratios of th[illegible] system inc[illegible] with the number of effects and with t[he] entra[inm]ent ratio of the thermo-compressor and decreas[illegible] with the top [illegible] temperature.
(3) Energy analysis reve[illegible] that the therm[al va]por compression desalination plant [illegible]C) is [th]e most energy-efficient when compared with [illegible] mech[ani]cal vapor compression (MVC) and multi-effect boiling [illegible] ones.
(4) The sub-s[illegible] mos[illegible] pons[illegible] for energy destruction in all thre[illegible] esa[illegible] tion sy[illegible] investigated is the first effect, beca[illegible] of the [hi]gh tempe[ra]ture of its heat input. In the TVC syst[illegible] this [illegible] 39%, with the second highest energy defect [illegible] that of the thermo-compressor, equal to 17%.
(5) Energy lo[illegible] can be significantly reduced by increasing the number of [illegible] s and the thermo-compressor entrainment ratio (vapor taken from evaporator and compressed by ejector), or by decreasing the top brine and first-effect heat input temperatures.

Finally, Eltawil et al. [1] explained simply the basic theory of a VC process that, the input energy is accomplished by a work device (compressor). Seawater feed is initially heated in a liquid/liquid heat exchanger by the blow down and product streams and further warmed by thermal rejection from the compressor. The feed then enters the evaporator where it evaporates. The produced vapor in the evaporator is then passed to the vapor compressor where it is compressed; its temperature is being raised in this process. It then passed to the heater/condenser secti[on] whe[re it i]s condensed to product, see Fig. 7.

Table 3
Relative power requirements of desalination processes (assumed conversion efficiency of electricity generation of 30% [2]).

Process	Heat input (kJ/kg of product)	Mechanical power input (kWh/m^3)	Prime energy cons. (kJ/kg)[a]
MSF	294	2.5:4	338.4
MEB	123	2.2	149.4
VC	N/A	8:16	192
ED	N/A	12	144
Solar still	2330	0.3	2333.6
RO	N/A	5:13	120
ER-RO	N/A	4: 6	60

2.1.4. *Freezing*

This one of commonly [use]d freezing m[ethods] [w]hich use butane as secondary refrigera[nt. The] freezi[ng p]rocess i[s ba]sed on the following fact. Freezing a sal[illegible] solu[tion] causes crystals of pure water to nucleate and gro[w, le]aving [th]e concen[tra]te behind. Seawater feed is pre-cooled b[y h]eat exchan[ge b]etw[een] the product water and the waste brine[illegible]. The feed t[hen e]nters the freezer where liquid butane is [bu]bble[d thr]ough the seawater feed. The butane vaporizes and lowers the [wat]er temperature. This result in formation of [illegible] ice crystals [illegible] ore concentrated brine. Approximately o[ne]-half of the seawater is frozen into ice crystals. The ice-brine [slu]rry is then [pu]mped to a washer-melter where the slurry rises [with]in the was[her] and the ice crystals are compacted into a porous be[d of] ice wh[ich] is removed upward by a slight positive pressure caus[illegible] brine flowing through the bed and outward through screens positioned near the middle of the column. The rising ice [illegible] washed with less than 5% of the total product. The ice is then removed by means of mechanical scrapper into the melter. The butane vapor which contains the heat removed to form the ice is compressed in the primary compressor and then introduced into the melter where it condenses on the ice. Heat is given up and the ice is melted. The condensed butane and the product water flow together to descanting unit where the two liquids are separated.

The relative power requirements for the various types of desalination processes are listed in Tables 3 and 4. It is clear from the data presented in the table that thermal desalination process requires more total energy than RO processes per unit volume of treated water [1,2].

2.1.5. *Solar distillation*

The other non-conventional methods to desalinate brackish water or seawater, is solar distillation. Comparatively, this requires a simple technology which can be operated by non-skilled workers. Also due to the low maintenance requirement, it can be used anywhere with lesser number of problems. It utilizes the evaporation and condensation processes. The principle of solar distillation is based on the fact that glass and other transparent materials have the property of transmitting incident short-wave solar radiation. This radiation can pass through the glass into the still and heat the water contained in it [10–21].

A representative example of direct collection systems is the conventional solar still, which uses the greenhouse effect to evaporate salty water. It consists of a basin, in which a constant amount of seawater is enclosed in a 'V'-shaped glass envelope, see Fig. 8. The sun's rays pass through the glass roof and are absorbed by the blackened bottom of the basin. As the water is heated, its vapor pressure is increased. The resultant water vapor is condensed on the underside of the roof and runs down into the troughs, which conduct the distilled water to the reservoir. The still acts as a heat trap because the roof is transparent to the incoming sunlight, but it is opaque to

Table 4
Relative power requirements of desalination processes [1].

Process	Gain output ratio (GOR)	Electric energy. cons. (kWh/m^3)	Thermal energy Cons. (kWh/m^3)	Total energy cons. (kWh/m^3)
MSF	08:12	3.25:3.75	6.75:9.75	10.5:13
MED	08:12	2.5:2.9	4.5:6.5	7.4:9
MED-TVC	08:14	2:2.5	6.5:12	9:14
MVC	N/A	9.5:17	N/A	9.5:17
BWRO	N/A	1:2.5	N/A	1:2.5
SWRO	N/A	4.5:8.5	N/A	4.5:8.5

the infrared radiation emitted by the hot water (greenhouse effect). The roof encloses the entire vapor, prevents losses, and keeps the wind from reaching and cooling the salty water.

Fig. 8 shows the various components of a conventional double slope symmetrical solar distillation unit (also known as roof type or greenhouse type solar still). The still consists of an air tight basin, usually constructed out of concrete/cement, galvanized iron sheet (GI) or fiber reinforced plastic (FRP) with a top cover of transparent material like glass or plastic. The inner surface of the base known as the basin liner is blackened to absorb efficiently the solar radiation incident on it. There is a provision to collect distillate output at the lower ends of top cover. The brackish or saline water is fed inside the basin for purification using solar energy.

The stills require frequent flushing, which is usually done during the night. Flushing is performed to prevent salt precipitation [2]. Design problems encountered with solar stills are brine depth, vapor tightness of the enclosure, distillate leakage, methods of thermal insulation, and cover slope, shape and material [1,2]. A typical still efficiency, defined as the ratio of the energy utilized in vaporizing the water in the still to the solar energy incident on the glass cover, is 35% (maximum) and daily still production is about 3–4 L/m^2 [1,2].

Several attempts have been made to use cheaper materials such as plastics. These are less breakable, lighter in weight for transportation, and easier to set up and mount. Their main disadvantage is their shorter life [2]. Many variations of the basic shape shown in Fig. 8 have been developed to increase the production rates of solar stills [2]. Some of the most popular ones are shown [illegible]

The classification of solar distillation systems has been studied by many authors [1,2,10,11]. On the basis of various modifications and mode of operations introduced in conventional solar stills; these are classified as passive and active. In case of active solar stills, an extra-thermal energy by external equipment is fed into the basin of passive solar still for faster evaporation. The external equipment may be a collector/concentrator panel, waste thermal energy from any chemical/industrial plant or conventional boiler [1,2]. If no such external equipment is used, then that type of solar still is known as passive solar still. Different types of solar still available in the literature are conventional solar stills, single-slope solar still with passive condenser, double condensing chamber solar still, vertical solar still, conical solar still, inverted absorber solar still and multiple effect solar still [2].

The following other techniques to increase the production of stills has been recommended as reviewed by Kalogirou [2]:

1. using various dyes to enhance performance. The dyes darken the water and increase its solar radiation absorptivity. With the use of black napthalamine at a concentration of 1725 ppm, the still output could be increased by as much as 29%. The use of these dyes is safe because evaporation in the still occurs at 60 °C, whereas the boiling point of the dye is 180 °C.
2. Increasing the production of a still by lining its bed with charcoal. The presence of charcoal leads to a marked reduction in start-up time. Capillary action by the charcoal partially immersed in a [illegible] and its reasonably black color and surface roughness reduce the system thermal inertia.
3. Developing a double-basin type solar still. This still provides a 4[illegible]5% increase in fresh water produced as compared to a standard still depending on the intensity of solar radiation. The idea is to use two stills, one on top of the other, the top one being made completely from glass or plastic and separated into small parts. Similar results were obtained by other two researches, who compared the performance of single and double-basin solar stills [2].
4. Developing a simple multiple-wick-type solar still in which blackened wet jute cloth forms the liquid surface. Jute-cloth pieces of increasing lengths were used, separated by thin black polyethylene sheets resting on foam insulation. Their upper edges are dipped in a saline water tank, where capillary suction provides a thin liquid sheet on the cloth, which is evaporated by solar energy. The results showed a 4% increase in still efficiency above conventional stills.

Evidently, the distance of the gap between the evaporator tray and the condensing surface (glass cover) has a considerable influence on the performance of a solar still which increases with decreasing gap distance. This led to the development of different categories of solar stills, namely, the cascaded type solar still [2]. This consists mainly of shallow pools of water arranged in cascade, as shown in Fig. 10, covered by a slopping transparent enclosure.

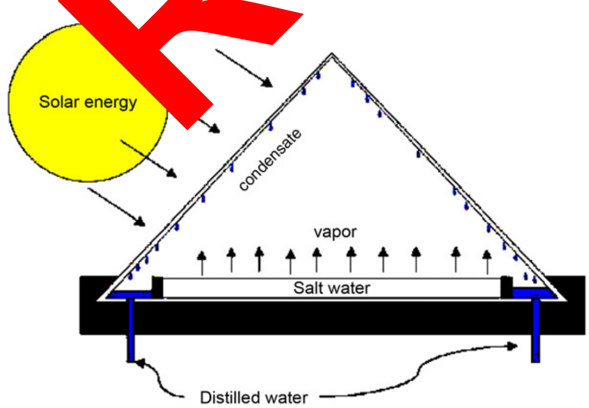


Fig. 8. The basic design of a solar distillation [1].

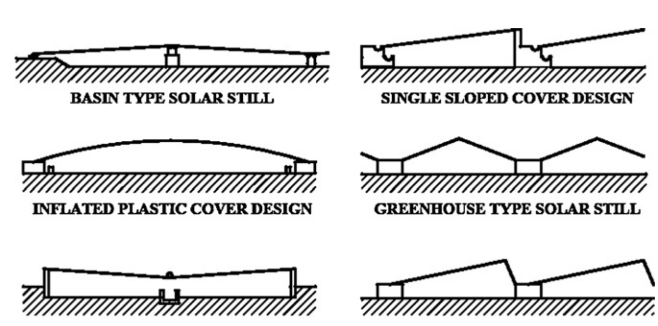


Fig. 9. Common designs of solar stills [2].

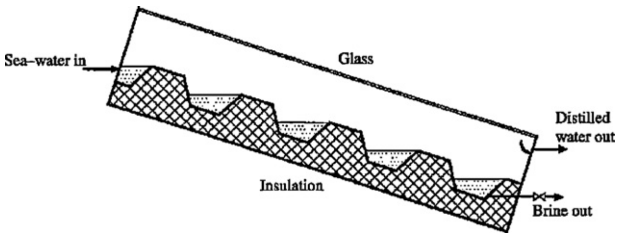


Fig. 10. Schematic of a cascaded solar still [2].

The evaporator tray is usually made of a piece of corrugated aluminum sheet (similar to the one used for roofing) painted flat black.

The meteorological parameters, namely wind velocity, solar radiation, sky temperature, ambient temperature, salt concentration, algae formation on water and mineral layers on basin liner affect significantly the performance of solar stills. For better performance of a conventional solar still, the following modifications were suggested by various researchers [2]:

- Reducing bottom loss coefficient.
- Reducing water depth in basin/multi-wick solar still.
- Using reflector.
- Using internal and external condensers.
- Using back wall with cotton cloth.
- Use of dye.
- Use of charcoal.
- Use of energy storage element.
- Use of sponge cubes.
- Multi-wick solar still.
- Condensing cover cooling.
- Inclined solar still.
- Increasing evaporative area.

It is observed that there is about a 10–[illegible] chang[illegible] overall daily yield of solar stills due to variations in cl[illegible]ic a[illegible] parameters within the expected range[illegible]

The general comments about usa[illegible] solar stil[illegible] been mentioned by many authors as revie[illegible] Kalogirou [illegible] Generally, the cost of water produced in so[illegible] disti[illegible]on systems depends on the total capital investme[illegible] build the [illegible]t, the maintenance requirements, and the a[illegible]unt of water pr[illegible]ed. No energy is required to operate th[illegible]ar sti[illegible] unless pumps are used to transfer the water from t[illegible]. Th[illegible] the major share of the water cost in solar distillation is t[illegible] amortiz[illegible]n of the capital cost. The production ra[illegible]opor[illegible]l to t[illegible] area of the solar still, which means the[illegible]t p[illegible]nit o[illegible] produced is nearly the same regardle[illegible] of the s[illegible] of the in[illegible]allation. This is in contrast with conditio[illegible] fr[illegible]plies as well as for most other desalination me[illegible] where the capital cost of equipment per unit of capacity decre[illegible] as the capacity increases. This means that solar distillation may [illegible]ore attractive than other methods for small sizes. Also, it has been reported that the solar distillation plants having capacity less than 200 m^3/day are more economical than other plants.

In conclusion, solar stills are the cheapest, with respect to their initial cost, of all available desalination systems in use today. This is a direct collection system, which is very easy to construct and operate. The disadvantage of solar stills is the very low yield, which implies that large areas of flat ground are required. It is questionable whether solar stills can be viable unless a cheap, desert-like land is available near the sea. However, obtaining fresh water from saline or brackish water with solar stills is useful for arid and remote areas, where water supply is available.

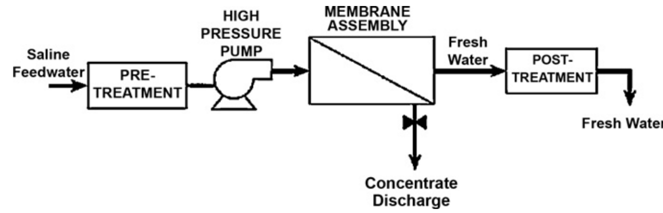


Fig. 11. Schematic of a simple reverse osmosis (RO) system [1].

2.2. Membrane processes

The thermal processes can be sub[illegible]ed in[illegible] following processes.

2.2.1. Reverse osmosis (RO[illegible]

The RO system depe[illegible] on th[illegible] prope[illegible] semi-permeable membranes which, w[illegible] used [illegible]eparate w[illegible]er from a salt solution, allow fresh w[illegible]ter [illegible]to the [illegible]ne compartment under the influence o[illegible]otic [illegible]ure. If [illegible]ressure in excess of this value is appli[illegible] the salty so[illegible]esh water will pass from the brine into [illegible] w[illegible] compartm[illegible] Theoretically, the only energy requireme[illegible] is to [illegible]p the feed water at a pressure above the osmot[illegible]essure. In p[illegible]ice, higher pressures must be used, typica[illegible]0 bar, in orde[illegible] have a sufficient amount of water pass [illegible]ough a unit area of membrane [2]. With reference to Fig. 11, [illegible] feed is pre[illegible]rized by a high-pressure pump and made to flow a[illegible]s the me[illegible]ane surface. Part of this feed passes through the me[illegible]ne w[illegible]e the majority of the dissolved solids are removed. The re[illegible], together with the remaining salts, is rejected at high [illegible]essure. In larger plants, it is economically viable to recover the [illegible] brine energy with a suitable brine turbine. Such systems are called energy recovery reverse osmosis (ER-RO) systems.

Solar energy can be used with RO systems as a prime mover source driving the pumps [1] or with the direct production of electricity through the use of photovoltaic panels [1–3]. Wind energy can also be used as a prime mover source. As the unit cost of the electricity produced from photovoltaic cells is high, photovoltaic-powered RO plants are equipped with energy-recovery turbines. The output of RO systems is about 500–1500 L/day per square meter of membrane, depending on the amount of salts in the raw water and the condition of the membrane. The membranes are in effect very fine filters, and are very sensitive to both biological and non-biological fouling. To avoid fouling, careful pre-treatment of the feed is necessary before it is allowed to come in contact with the membrane surface.

One method used recently for the pre-treatment of seawater before directed to RO modules is nana-filtration (NF). NF is primarily developed as a membrane softening process which offers an alternative to chemical softening. The main objectives of NF pre-treatment are [2]:

1. Minimize particulate and microbial fouling of the RO membranes by removal of turbidity and bacteria.
2. Prevent scaling by removal of the hardness ions.
3. Lower the operating pressure of the RO process by reducing the feed-water total dissolved solids (TDS) concentration.

The most important results obtained by many authors were reviewed and summarized as follows [1–8]:

1. Analysis of a system using an RO desalination unit driven by PV panels or from a solar–thermal plant. It is concluded that due to the high cost of the solar equipment the cost of fresh water is

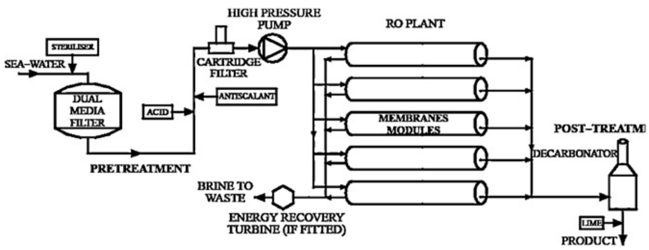


Fig. 12. Principle of operation of a reverse osmosis (RO) system [2].

about the same as with an RO system operated from the main power supply.

2. Performing an energy analysis of a 7250 m^3/day reverse osmosis (RO) desalination plant in California. The analysis of the system was conducted by using actual plant operation data. The RO plant is described in detail, and the energies across the major components of the plant are calculated and illustrated using energy flow diagrams in an attempt to assess the energy destruction distribution. It was found that the primary locations of energy destruction were the membrane modules in which the saline water is separated into the brine and the permeate, and the throttling valves, where the pressure of liquid is reduced, pressure drops through various process components, and the mixing chamber, where the permeate and blend are mixed. The largest energy destruction occurred in the membrane modules, and this amounted to 74.1% of the total energy input. The smallest energy destruction occurred in the mixing chamber. The mixing accounted for 0.67% of the total energy input and presents a relatively small fraction. The second law efficiency of the plant was calculated to be 4.3%, which seems to be low. It is shown that the second law of efficiency can be increased to 4.9% by introducing a pressure exchanger with two throttling valves on the brine stream, and this saved 19.8 kW of electricity by reducing the pumping power of the incoming saline water.

RO process is based on what is known as osmotic pressure. If the seawater solution is fed to one side of a membrane at pressure greater than the osmotic pressure, pure water will migrate from the feed through the membrane to the other side. In the mean time the concentrated brine is extracted from the input side of seawater as indicated in Figs. 11 and 12. The most used type of membranes is spiral wound and hollow fine fiber. They are very sensitive to fouling both biological and non-biological; therefore RO plants generally require pretreatment system.

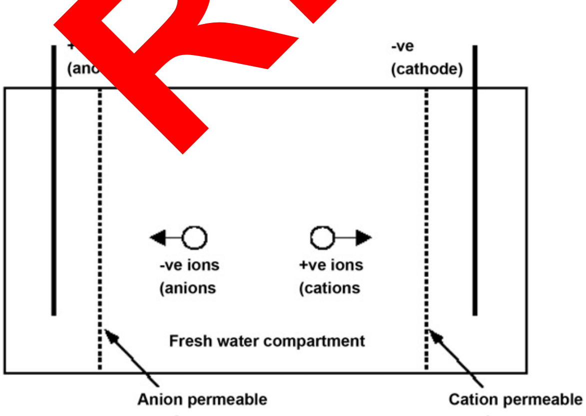


Fig. 13. Principle of operation of electro-dialysis (ED) [2].

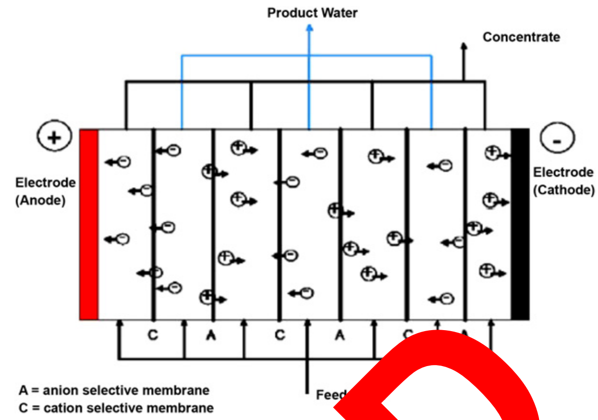


Fig. 14. Principle of electro dialysis under constant DC current field [1].

2.2.2. Electro-dialysis (ED)

This system, shown schematically in Fig. 13, works by reducing salinity by transferring ions from the feed water compartment, through membranes, under the influence of an electrical potential difference. The [illegible] utilizes a dc electric field to remove salt ions in the brackish water. Saline feed-water contains dissolved salts separated into positively charged sodium and negatively charged chloride ions. These ions will move toward an appositively charged electrode immersed in the solution, i.e. positive ions (actions) will go to the negative electrode (cathode) and negative ions (anions) to the positive electrode (anode). If special membranes, alternatively cation-permeable and anion-permeable, separate the electrodes, the center gap between these membranes will be depleted of salts [2]. In an actual process, a large number of alternating cation and anion membranes are stacked together, separated by plastic flow spacers that allow the passage of water. The streams of alternating flow-spacers are a sequence of diluted and concentrated water which flow in parallel to each other. To prevent scaling, inverters are used which reverse the polarity of the electric field every about 20 min.

As the energy requirements of the system are proportional to the water's salinity, ED is more feasible when the salinity of the feed water is not more than about 6000 PPM of dissolved solids. Similarly, due to the low conductivity, which increases the energy requirements of very pure water, the process is not suitable for water of less than about 400 PPM of dissolved solids.

As the process operates with DC power, solar energy can by used with electro dialysis by directly producing the voltage difference required with photovoltaic (PV) panels.

The electro-dialysis process is based on the fact that when a DC current is passed through an ionic solution, positive ions will migrate to the cathode and negative ions will migrate to the anode. If we place between the anode and cathode alternately, membranes which will allow only the passage of positive ions and membranes which will allow only the passage of negative ions then alternate regions of high salinity and low salinity will be created between the appropriate membranes. The product water can then be moved from the low salinity region and the brine from the high salinity region. Fig. 14 shows the process arrangement.

3. Renewable energy systems (RES)

All the energy sources we are using today can be classified into two groups; renewable and non-renewable. Renewable energy is derived from natural processes that are replenished constantly (electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, bio-fuels and hydrogen derived from renewable resources) [22]. Non-renewable

Table 5
The annual horizontal solar energy available in some countries [24].

Country	Annual solar energy (kWh/m^2)	Peak radiation (W/m^2)
Yemrn	2170	940
Saudi Arabia	2160	940
Oman	2140	930
Egypt	2050	1030
Jordan	2050	1020
Libya	2010	1040
U.A. Emirates	1980	910
Israel	1930	1010
Syria	1910	1040
Malta	1900	1040
Morocco	1860	960
Algeria	1840	950
Tunisia	1750	980

energy is energy sources that cannot replenish in the near future such as coal, petroleum and natural gas. Renewable and non-renewable energy sources can be used to produce secondary energy sources including electricity and hydrogen

This section presents a review of the possible systems that can be used for renewable energy collection and transformation into usable energy, which may be used to power desalination equipment. These cover solar energy which includes thermal collectors, solar ponds and photovoltaic, wind energy and geothermal energy. Solar energy thermal collectors include stationary and tracking collectors. Stationary collectors include the flat-plate and the evacuated tube, whereas concentrating collectors are further divided into imaging and non-imaging collectors like the parabolic trough and compound parabolic, respectively.

Today, there exist many large solar plants with output i[illegible]he range of MW for producing electricity or process heat. The firs[illegible]mercial solar plant was installed in Albuquerque, New Mexico[illegible]A, in 1979. It consisted of 220 heliostats and had an output of 5 [illegible]. The second was erected at Barstow, CA, USA, wit[illegible]al therm output of 35 MW. Most of the solar plants produ[illegible]ect[illegible]y and/o[illegible] process heat for industrial use and they provi[illegible]uperh[illegible]ed steam of 673 K. Thus, they can provide electricity [illegible]/or [illegible] small capacity conventional desalinati[illegible]plant[illegible]n by thermal or electrical energy [22,23].

3.1. *Potential of solar energy*

Energy experts expec[illegible]t in the year 205[illegible]er 50% and 80% of all electricity could b[illegible]erate[illegible] renewable energy [9]. Among the potential source[illegible]ren[illegible]ble energy, solar thermal power plants are considered t[illegible]e of the[illegible]st economic.

The under[illegible]g of t[illegible]tech[illegible]ogy and its associated challenges wil[illegible]ovid[illegible]suitab[illegible]s to recognize advantages and drawba[illegible]The An[illegible]al horizon[illegible]solar energy available (kWh/m^2) and rela[illegible]eal[illegible]^2) in some countries is given in Table 5 [24]. The fo[illegible]g sections will outline various existing solar technologies [22,2[illegible].

3.2. *Photovoltaic (PV) energy*

Photovoltaic cells are semi-conductor devices, which converts sunlight energy directly to electrical energy. Conventional photovoltaic cells are made of crystalline silicon that has atoms arranged in a three dimensional array, making it an efficient semiconductor. Although, this material is most commonly used for generation of electricity, it also has associated drawbacks, such as high material costs for silicon, costly processes for purifying silicon and manufacturing wafer, additional processes for assembly of modules and the bulky and rigid nature of the photovoltaic panels. Fig. 15 depicts a typical PV cell under illumination [22].

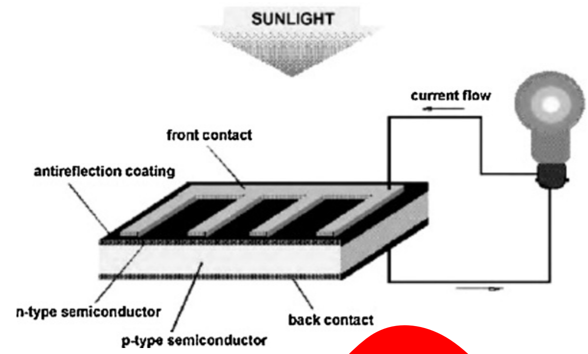


Fig. 15. Photovoltaic cell u[illegible]illuminati[illegible].

Becquerel had discovere[illegible]e photo[illegible]ic eff[illegible]n selenium in 1839. The conversion effi[illegible]cy of the new[illegible]ells developed in 1958 was 11% althoug[illegible]e cost[illegible]s prohib[illegible]ely high ($1000/W) [22]. The first practical a[illegible]ca[illegible]n of sola[illegible]cells was in space, where cost was not a b[illegible]r as n[illegible]er sou[illegible]f power is available.

PV equipm[illegible] has no m[illegible]g[illegible]s and as a result requires minimal m[illegible]ce and has [illegible]g life. It generates electricity without pr[illegible]ducing[illegible]issions of greenhouse or any other gases, and its op[illegible]ation is virtu[illegible]ilent.

[illegible]ll consists of t[illegible]or more thin layers of semi-conducting [illegible]erial, most commonly silicon. When the silicon is exposed to [illegible]t, electrica[illegible]harges are generated and this can be conducted a[illegible] by metal[illegible]tacts as direct current (DC). The electrical output fr[illegible]single[illegible]is small, so multiple cells are connected together and e[illegible]ted (usually glass covered) to form a module (also [illegible]alled a panel).

[illegible]PV panel is the principle building block of a PV system and any n[illegible]mber of panels can be connected together to give the desired electrical output. This modular structure is a considerable advantage of the PV system, where further panels can be added to an existing system as required.

Photovoltaic (PV) cells are made of various semiconductors, which are materials that are only moderately good conductors of electricity. The materials most commonly used are silicon (Si) and compounds of cadmium sulphide (CdS), cuprous sulphide (Cu_2S), and gallium arsenide (GaAs). These cells are packed into modules which produce a specific voltage and current when illuminated. PV modules can be connected in series or in parallel to produce larger voltages or currents. Photovoltaic systems can be used independently or in conjunction with other electrical power sources. Applications powered by PV systems include communications (both on earth and in space), remote power, remote monitoring, lighting, water pumping and battery charging. The global installed capacity of photovoltaic at the end of 2002 was near 2 GW_p [22].

PV applications are: either Stand-alone applications or Grid-connected systems. Standalone PV systems are used in areas that are not easily accessible or have no access to main electricity. A standalone system is independent of the electricity grid, with the energy produced normally being stored in batteries. A typical stand-alone system would consist of PV module or modules, batteries and charge controller. An inverter may also be included in the system to convert the direct current (DC) generated by the PV modules to alternating current (AC) required by normal appliances.

For grid-connected systems. Nowadays, it is usual practice to connect PV systems to the local electricity network. This means that during the day, the electricity generated by the PV system can either be used immediately (which is normal for systems installed in offices, other commercial buildings and industrial applications), or can be sold to one of the electricity supply companies (which is more common for domestic systems, where the occupier may be

out during the day). In the evening, when the solar system is unable to provide the electricity required, power can be bought back from the network. In effect, the grid is acting as an energy storage system, which means the PV system does not need to include battery storage.

For PV system configuration. The PV array consists of a number of individual photovoltaic modules connected together to give a suitable current and voltage output.

Common power modules have a rated power output of around 50–80 W each. As an example, a small system of 1.5–2 kWp may therefore comprise some 20–30 modules covering an area of around 15–25 m^2, depending on the technology used and the orientation of the array with respect to the sun.

Most power modules deliver direct current (DC) electricity at 12 volts (V), whereas most common household appliances and industrial processes operate with alternating current (AC) at 240 or 415 V (120 V in the United States). Therefore, an inverter is used to convert the low voltage DC to higher voltage AC. Numerous types of inverters are available, but not all are suitable for use when feeding power back into the mains supply.

Other components in a typical grid-connected PV system are the array mounting structure and the various cables and switches needed to ensure that the PV generator can be isolated.

Attractiveness of the PV technology is low maintenance, and no pollution, and has positioned PV to be the preferred power technology for many remote applications for both space and on the ground. Photovoltaic (PV) technology is expected to be a leading technology to solve the issues concerning the energy and the global environment due to several advantages of the PV system. The installed, unsubsidized costs, now coming close to $0.2/kWh in the best applications while average electric rates from utilities are less than $0.1/kWh [22,23]. Although, photovoltaic electricity is three to five times more expensive than other conventional grid power systems, PV is turning into a mainstream. The average cost for PV technology in 2006 was roughly $7–10 per peak watt installed [22]. On the other hand, the average module cost is about $4.[illegible]/W on November 2009 [22]. The lowest retail price for multi-crystalline silicon solar module is $2.48 per watt from a US retailer and the lowest retail price for a monocrystalline silicon module is $2.70 per watt, from an Asian retailer [9]. Sun Power Corporation, a leader in PV industry is currently offers PV modules at 18% peak efficiency. However, climatic effects such as dirt accumulation and temperature rise as well as aging, which causes a gradual increase of the device's internal leakage conductance, and consequently lowers the efficiency.

3.3. *Thin-film photovoltaic*

PV thin film technology are usually divided into mono-crystalline, multi-crystalline silicon and amorphous silicon cells [22,23].

Mono-crystalline silicon cells are made from very pure mono-crystalline silicon. The silicon has a single and continuous crystal lattice structure with almost no defects or impurities. The principle advantage of mono-crystalline cells is their high efficiency, typically around 15%, although the manufacturing process required to produce mono-crystalline silicon is complicated, resulting in slightly higher costs than other technologies.

Multi-crystalline silicon cells are produced using numerous grains of mono-crystalline silicon. In the manufacturing process, molten polycrystalline silicon is cast into ingots; these ingots are then cut into very thin wafers and assembled into complete cells. Due to the simpler manufacturing process, multi-crystalline cells are cheaper to produce than mono-crystalline ones. However, they tend to be slightly less efficient, with average efficiencies of around 12%.

Amorphous silicon cells are composed of silicon atoms in a thin homogenous layer rather than a crystal structure. Amorphous silicon absorbs light more effectively than crystalline silicon, so the cells can be thinner. For this reason, amorphous silicon is also known as a 'thin film' PV technology. Amorphous silicon can be deposited on a wide range of substrates, both rigid and flexible, which makes it ideal for curved surfaces and 'fold-away' modules. Amorphous cells are, however, less efficient than crystalline based cells, with typical efficiencies of around 6%, but they are easier and therefore cheaper to produce. Their low cost makes them ideally suited for many applications, where high efficiency is not required and low cost is important. Amorphous silicon (a-Si) is a glassy alloy of silicon and hydrogen (about 10%). Several properties make it an attractive material for thin-film solar cells:

1. Silicon is abundant and environmentally safe.
2. Amorphous silicon absorbs sunlight extremely well, so that only a very thin active solar cell layer is required (about 1 mm as compared to 100 mm or so for crystalline solar cells), thus greatly reducing solar-cell material requirements.
3. Thin films of a-Si can be deposited directly on inexpensive support materials such as glass, sheet steel, or plastic foil.

Other thin films which are promising materials such as cadmium telluride (CdTe) and copper indium diselenide (Cu In Se_2) are now being used for PV modules. The attraction of these technologies is that they can be manufactured by relatively inexpensive industrial processes, in comparison to crystalline silicon technologies, yet they typically offer higher module efficiencies than amorphous silicon.

Photovoltaic panels or modules are designed for outdoor use in such harsh conditions as marine, tropic, arctic, and desert environments. The choice of the photovoltaically active material can have important effects on system design and performance. Both the composition of the material and its atomic structure are influential.

The atomic structure of a PV cell can be single-crystal (monocrystalline), multi-crystalline, or amorphous. The most commonly produced PV material is crystalline silicon, either polycrystalline or in single-crystals.

A module is a collection of PV cells that protects the cells and provides a usable operating voltage. PV cells can be fragile and susceptible to corrosion by humidity or fingerprints and can have delicate wire leads. Also, the operating voltage of a single PV cell is less than 1 V, making it unusable for many applications. Depending on the manufacturer and the type of PV material, modules have different appearances and performance characteristics. Also, modules may be designed for specific conditions, such as hot and humid climates. Nowadays, the panels come in a variety of shapes like roof-tiles made from amorphous silicon solar cells.

Usually, the cells are series-connected to other cells to produce an operating voltage around 14–16 V. These strings of cells are then encapsulated with a polymer, a front glass cover, and a back material. Also, a junction box is attached at the back of the module for convenient wiring to other modules or other electrical equipment.

Cells made of amorphous silicon, cadmium telluride, or copper indium diselenide are manufactured on large pieces of material that become either the front or the back of the module. A large area of PV material is divided into smaller cells by scribing or cutting the material into electrically isolated cells.

It is evident that since the past 15–20 years various thin-film technologies have been under development for reducing the amount of light absorbing material required in producing a solar cell. Since silicon is the key contributor to the cost of PV technology, using less silicon will have a considerable effect on the cost reduction of the PV technology.

Conversion efficiency is one major metric for solar material, which represents how much of the sun's energy the material can convert into electricity. Today, the laboratory efficiency of the amorphous silicon (a-Si) is 12.3%, cadmium telluride (CdTe) is 16.5% and copper indium gallium selenide (CIGS) is 19.9% [22,23].

Advantages of Thin Film Technologies over Conventional Crystalline Silicon are lower cost of production than conventional silicon processes, lower production facility cost per watt, use of far less material, as little as 1/500th the amount used in standard silicon cells, and lower energy payback. It also produces more useable power per rated watt, provides superior performance in hot and overcast climates, has the ability to be attractively integrated into buildings and produces the lowest cost of power. The thin-film module manufacturing cost decreased to 98 cents per watt, breaking the $1 per watt price barrier [22,23]. Although, thin-film cells are not as efficient as conventional crystalline silicon-especially as they are not used in tandem devices, it is believed that thin-film will be a dominant PV technology in the future. Many also believe that, the likelihood of significant reduction of module cost has many opportunities to increase the efficiency that surely will reduce the overall cost of thin-film technology.

3.4. Concentrating photovoltaic

Concentrating photovoltaic (CPV) systems uses a large area of lenses or mirrors to focus a large area of sunlight on a small photovoltaic cells, which converts sunlight energy into electrical energy in the same way that the conventional photovoltaic technology does The attractiveness of the CPV technology over the standard PV technology is that it uses less semi-conducting material by re[illegible]lacing most of the PV cell area with a set of reflectors in o[illegible] reduce the cost. Additionally, increasing the concentration [illegible]tio will improve the performance of general photovoltaic materia[illegible]s shown in Fig. 16.

Concentrating photovoltaic technology off[illegible] [illegible]ollowi[illegible] advantages [9]:

(a) Potential for solar cell efficiencies [illegible]ter th[illegible]%.
(b) No moving parts.
(c) No intervening heat transfer [illegible]
(d) Near-ambient temperature [illegible]eratio[illegible]
(e) No thermal mass and a [illegible] response.
(f) Reduction in the cost [illegible]cells relative to o[illegible]s.
(g) Scalability to a ra[illegible] of size[illegible]



Fig. 16. A concentrating photovoltaic system uses a dense array of high-efficiency silicon cells [22].

Despite the advantages of CPV technologies, their application has been limited by the complexity and due to the cost of focusing, tracking and cooling equipment; it is now only reaching commercial viability. Even if using expensive cells, a CPV system with concentration ratio of 500 (or 500 suns) generally uses 1/500, the amount of PV cell surface area as does conventional PV. So the price of the PV cell constitutes a smaller cost consideration for CPV. Energy Innovations and SolFocus are two leading companies pursuing serious research efforts in CPV technology. SolFocus Company offered the cost of its Gen1 CPV system to become as low as $1/W at 1 GW production level [9]. Further, SolFocus Gen2 systems are expected to achieve 26% efficiency and a record cost less than $0.50/W [22,23].

4. Concentrating solar thermal p[illegible]er

Concentrating solar the[illegible]l power [illegible]ts h[illegible] the capability for thermal energy stor[illegible] and al[illegible]rnativ[illegible]d operation with fossil or bio-fuels, allo[illegible] them [illegible] provide fi[illegible]n power capacity on demand. The core [illegible]eld of l[illegible]e mirrors reflecting the captured sun ra[illegible] a sma[illegible]ceiver [illegible]ment, thus concentrating the solar radi[illegible] intensity [illegible] several 100 times and producing hig[illegible]ture heat a[illegible]veral 100 to over 1000 °C. This heat can be either [illegible] directly in a thermal power cycle based on stea[illegible]ines, gas tu[illegible]s or Stirling engines, or stored in molten sa[illegible]ete or phase-c[illegible]ge material to be delivered later to the [illegible]ver cycle for night-time operation [33].

The princip[illegible]f operation of a concentrating solar collector and o[illegible]CSP plant [illegible]rafted in Figs. 17 and 18, showing the option for co[illegible]ation of heat and power.

The[illegible] a simple power cycle for electricity generation only [illegible]f course also possible. From the point of view of a grid operator,

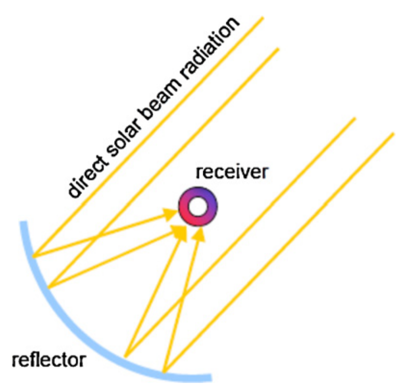


Fig. 17. Principle of a concentrated solar collector.

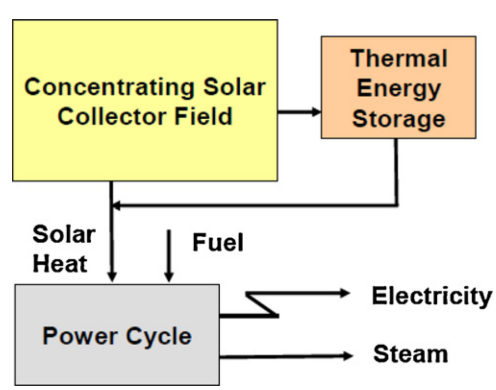


Fig. 18. Principle of a concentrating solar thermal power station for co-generation of electricity and process steam.

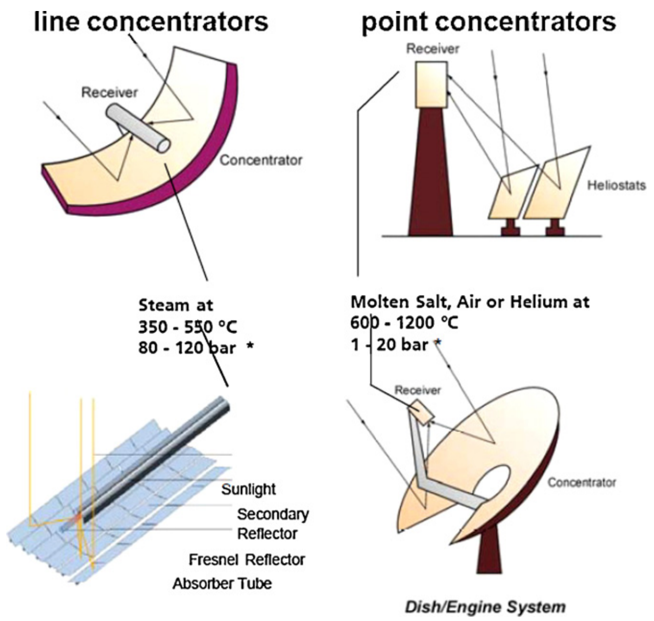


Fig. 19. Concentrating solar collector technology mainstreams: parabolic trough (top left), linear Fresnel (bottom left), central receiver solar tower (top right), and dish-Stirling engine (bottom right) [33].

Table 6
Cost of concentrated solar–thermal–electric technologies [22].

Specification/type	Solar dish–engine	Parabolic trough	Solar power tower
Standard plant size, MW	2.5–100	100	100
Max efficiency, %	30	24	22
Specific power, W/m^2	200	300	300
Basic plant cost, $/W	2.65	3.22	3.62
Total US installation, MW	0.118	354	[illegible]
Largest unit in the USA, MW	0.025	80	[illegible]
Demonstrated system, h	80,000	300,000	2000

CSP behaves just like any conventional fu[illegible]ed p[illegible]station, but with less or no fuel consumption, thus [illegible]g an impor[illegible]factor for grid stability and control in a future [illegible]y supply sy[illegible] based mainly on renewable energy sour[illegible]s. CSP[illegible]ts can be designed from 5 MW to several 100 MW [illegible] capacity [3[illegible]

For concentration of th[illegible]nlight, most syst[illegible]use curved or flat glass mirrors because [illegible]heir v[illegible]high reflectivity. Point focusing and line focusing co[illegible]r sy[illegible]ms are used, as shown in Fig. 19. These systems can only u[illegible]direct [illegible]ion of solar radiation, but not the diffu[illegible] of the [illegible]light[illegible]t cannot be concentrated by mirrors. Li[illegible]ocu[illegible] syste[illegible] easier to handle than point concentrat[illegible] system[illegible]but have a [illegible]ower concentration factor and hence achi[illegible]ow[illegible]es than point focusing systems. Therefore, line[illegible]entrating systems will typically be connected to steam cycle pow[illegible]tions, while point concentrating systems are additionally capable [illegible]riving gas turbines or combustion engines. Table 6 gives a comparison of the main features of solar thermal power technologies.

5. Different combination between RES and desalination systems

There are numerous renewable energy sources (RES)–desalination combinations have been identified and tested in the framework of ongoing research for innovative desalination processes [1,2,22]. Table 7 and Fig. 20 show the distribution of renewable energy powered desalination technologies [1]. Energy requirement in the form of thermal as well as electrical energy

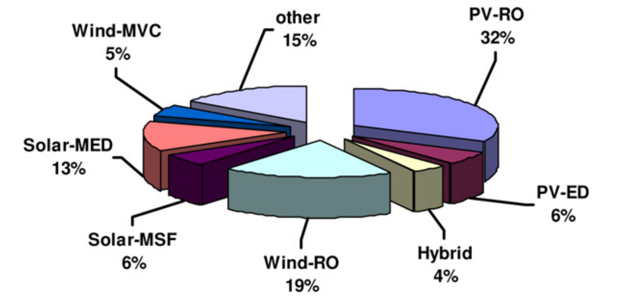


Fig. 20. Distribution of renewable energy powered desalination technologies [1].

can make up between 50% and 70% [illegible] the total [illegible]erating cost and it is thus not surprising that ma[illegible]f the large-[illegible]le thermal desalination plants are co-located with p[illegible]r stations [illegible] industries with thermal process energy w[illegible]e. The gl[illegible] ins[illegible]ed desalting capacity by process in 200[illegible] shown [illegible] Fig. 2[illegible]

5.1. Photovoltaic and [illegible]O (P[illegible]) [illegible]mbinati[illegible]

RO desalinat[illegible]unit can be [illegible] with different types of renewable en[illegible]y. [illegible] 8 summari[illegible]s several studies which were presented with variou[illegible]sible combinations and Table 9 presents the corr[illegible]ding costs. [illegible]own in Table 9, the cost of desalinated wat[illegible]pe[illegible]ds on few facto[illegible]ncluding plant capacity, RES/RO system [illegible]esign, feed water quality, site location, etc.

[illegible]re are ma[illegible] two PV driven membrane processes, reverse osm[illegible] (RO) a[illegible] electro-dialysis (ED). Both techniques are descr[illegible]bove[illegible]d from a technical point of view, PV as well as RO and ED a[illegible]mercially available technologies. At present time, [illegible]asibility of PV-powered RO or ED systems, as valid options f[illegible]ation at remote sites, has also been proven [2]. Indeed, [illegible]ere are commercially available standalone, PV powered desalination systems [2]. The main problem of these technologies is the high cost and, for the time being, the availability of PV cells. Many of the early PV-RO demonstration systems were essentially a standard RO system, which might have been designed for diesel or mains power, but powered from batteries that were charged by PV. This approach tends to require a rather large PV array for a given flow of product, due to poor efficiencies both in the standard RO systems and in the batteries. Large PV arrays and regular replacement of batteries would tend to make the cost of water from such systems rather high. Table 8 shows a selection of some brackish-water PV powered RO system.

Fig. 22 shows diagram of photovoltaic-powered reverse-osmosis (PV-RO) system to desalinate seawater without batteries. The system is operated from seawater and requires no batteries, since the rate of production of freshwater varies throughout the day according to the available solar power. Initial testing of the system, with the modest solar resource available in the UK, provided freshwater at approximately, 1.5 m^3/day. Nearer to the equator and with

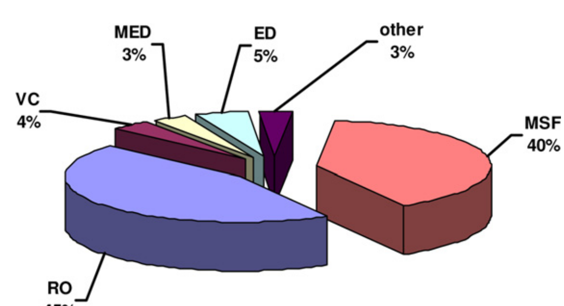


Fig. 21. Global installed desalting capacity by process [1].

Table 7
General combinations technologies of RES and desalination methods [1].

Renewable energy sources																				
1-Solar											2-Wind					3-Geothermal				
PV			Solar thermal								Shaft		Electricity			Electricity			Heat	
Electricity			Heat			Shaft			Electricity											
RO	ED	MVC	TVC	MED	MSF	MVC	RO	ED	RO	MVC	MVC	RO	RO	ED	MVC	RO	ED	MVC	TVC	MED	MSF

Table 8
Selection of some brackish-water PV-RO systems [1].

Location	Feed water (ppm)	Capacity (m^3/day)	PV (kW_p)	Battery (kWh)
Sadous Riyadh {Saudi Arabia}	5800	15	10	264
Haifa {Israel}	5000	3	3.5 plus 0[illegible]d	36
Elhamrawie {Egypt}	3500	53	18	200
Heelat ar Rakah {Oman}	1000	5	3.2[illegible]	9.6
White Cliffs {Australia}	3500	0.5	0[illegible]	None
Solarflow {Australia}	5000	0.4	[illegible]2	None

Table 9
Water cost for desalination by renewable energies [25].

Combination	Water	Plant capacity (m^3/day)	Water [illegible]S$/$m^3$)	Year
PV/BAT/RO	Seawater	12	27	1996
PV/BAT/RO		120	7.4	1996
PV/BAT/RO	Brackish water	250	[illegible].7	1991
PV/RO	Seawater	1.5	2.95	2003
WIND/BAT/RO	Brackish water	250	2.7	2003
WIND/GRID/RO	Seawater	300	1.8	2002
PV/GRID/RO	Seawater		1.9	2005

a PV array of only 2.4 kW_p, a software model of the system p[illegible] production of over 3 m^3/day throughout the year [1].

5.2. Concentrating solar thermal driven desalinatio[illegible]

The different configurations for desalin[illegible]n by c[illegible]entrated solar power are shown in Fig. 23(a–c).

A conceptual layout for a solar dis[illegible]sed [illegible] with power generation and RO desalination is s[illegible]n in Fig. 2[illegible]

The low temperature waste [illegible]shown as a[illegible]ut to the feed water as a reduction in RO [illegible]ergy [illegible]umption is achieved if the feed water temperature [illegible] raised (but [illegible] up to a limit which is determined by the me[illegible]ane characteris[illegible]nd other operating parameters). A mo[illegible]ation [illegible]this arrangement is described in

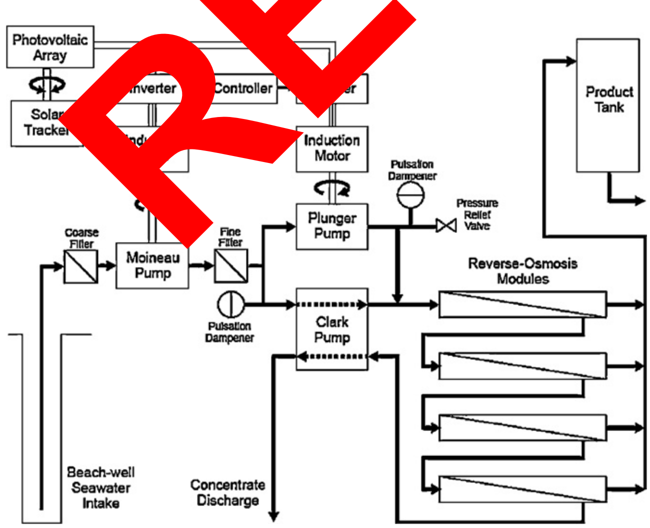


Fig. 22. PV-RO system to desalinate seawater without batteries [1].

[1,2]: steam is used primarily to power a steam turbine and gen[illegible] electricity, but is also extracted from the turbine (at reduced [illegible]e and temperature) and used to drive a booster pump, which provides part of the RO high pressure pumping demand.

5.3. Wind energy and RO (WIND/RO)

The electrical or mechanical energy required as primary energy input for the RO unit can be provided from a single wind turbine or a wind farm. However, reverse osmosis is the preferred technology due to the low specific energy consumption [1,2,25]. Because of the variability of wind speed, it is difficult to predict the energy output. So, appropriate power control and conditioning systems are required in order to match the ratio of power input to desalination load. The design of the control system is the most critical step in the design of a desalination RO unit powered by wind energy. There were a number of attempts to combine wind energy to the RO process. Several units have been installed and tested worldwide, however, these studies remain at the research level [26–30]. Therefore, this area suffers from lack of information and data in terms of expertise. On the other hand, the prospects of this combination are promising, mainly due to the low cost of wind energy, see Table 9.

Remote areas with potential of wind energy resources such as islands can employ wind energy systems to power seawater desalination for fresh water production. The advantage of such systems is a reduced water production cost compared to the costs of transporting the water to the islands or to using conventional fuels as power source. Different approaches for wind/desalination systems are possible. First, the wind turbines/desalination system are connected to a grid system. The second option is based on direct coupling of the wind turbine(s) and the desalination system. In this case, the desalination system is affected by power variations and interruptions caused by the power source (wind). These power variations, however, have an adverse effect on the performance and component life of certain desalination equipment. Hence, backup

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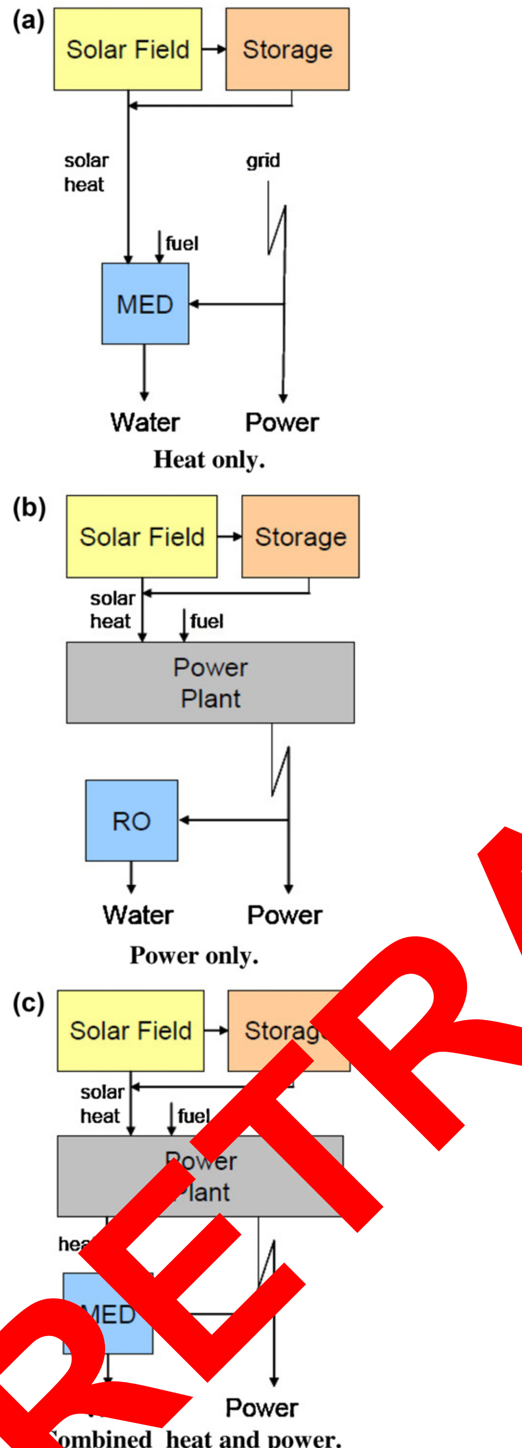


Fig. 23. (a) Heat only. [illegible]wer only. (c) Combined heat and power. Different configurations for desalination by concentrated solar power [33].

systems, such as batteries, diesel generators, or flywheels might be integrated into the system. Fig. 25 shows a schematic presentation of an RO desalination plant. The process takes place in ambient temperature. The only electrical energy required is for pumping the water to a relatively high operating pressure. The use of special turbines is for energy recovery from concentrate pressure. Operating pressures vary between 10 and 25 bars for brackish water and 50–80 bars for seawater. High pressure is needed to allow sufficient permeation at relatively high concentrations of the concentrating brine along the membrane axis located in the pressure vessel.

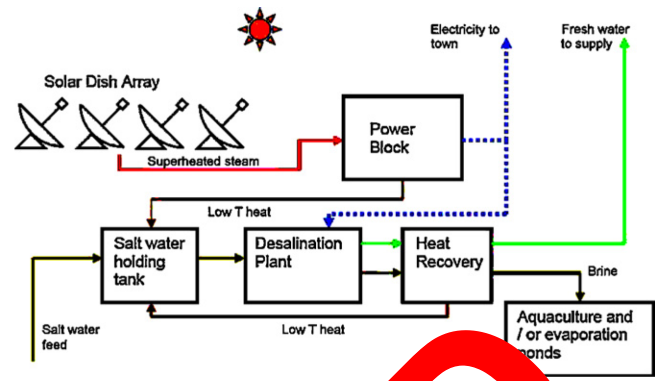


Fig. 24. Combined dish based solar thermal p[illegible]generation an[illegible] desalination [1].

Water recovery (permea[illegible]ater [illegible]ed by fe[illegible] water%) can go as high as 90.95% in the ca[illegible]t brack[illegible] water, while recovery is between 35 [illegible]50% i[illegible] case o[illegible]awater. Low recovery is obtained espe[illegible] in a relati[illegible]d sea, like the Red Sea or the Persian G[illegible]2].

The Europ[illegible]an Co[illegible]nity funded different research programs and demonstration proj[illegible]f wind desalination systems on Greek and S[illegible]slands. Other [illegible]d-driven RO systems are as follows. [illegible] installation of WIND/RO in the Middle East was started in 19[illegible] It is a 25 [illegible]day-plant connected to a hybrid wind–diesel sys[illegible] Besides t[illegible] in Drepanon, Achaia, near Patras (Greece), the opera[illegible]of oth[illegible]wind powered RO system started in 1995 [2]. Finally, [illegible] Commission (1998) presented other facilities at:

a. [illegible]la[illegible]of Suderoog (North Sea), with 6–9 m^3/day;
b. Ile du Planier, France Pacific Islands, with 0.5 m^3/h;
c. Island of Helgoland, Germany (2.4 m^3/h);
d. Island of St. Nicolas, West France (hybrid wind-diesel) and
e. Island of Drenec, France (10 kW wind energy converter).

In addition, interesting experimental research about the direct coupling of a wind energy system and a RO unit by means of shaft power has been carried out at the Canary Islands. Also, in Coconut Island (Oahu, Hawai), a brackish water desalination wind-powered RO plant was analyzed. The system was coupling directly the shaft power of a windmill with the high pressure pump. The result was 13 L/min can be maintained for wind speed of 5 m/s [2].

The ED process is interesting for brackish water desalination since it is able to adapt to changes of available wind power and it is most suitable for remote areas than RO. Modeling and experimental tests results of one of such system installed at the Gran Canaria, Spain is presented by [2]. The capacity range of this plant was 192–72 m^3/day.

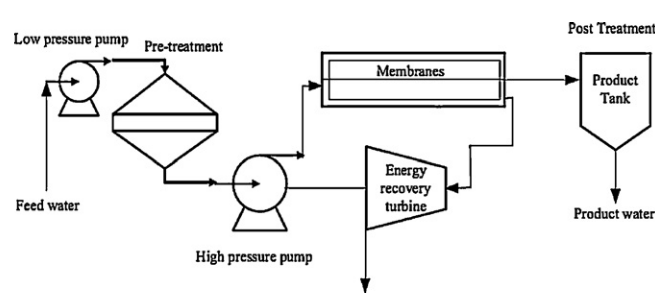


Fig. 25. Schematic presentation of a reverse osmosis desalination plant [1].

5.4. Hybrid units (PV/wind/batteries/RO)

Another interesting RES/RO configuration is the hybrid PV/wind/batteries/RO systems which have greater flexibility compared to previous configurations. Weiner et al. [31] studied, experimentally and numerically, an autonomous desalination plant with a capacity of 9 m^3/day supplied by solar photovoltaic and wind. A specially adapted code was developed to simulate the facility operation to allow an appropriate choice of components. The code continuously updates water level in the tank and battery charge state. Based on these two variables, a logical decision tree was designed to determine whether the combination of solar and wind energy can meet the burden of the unit or if an additional energy must be supplied by batteries or a generator auxiliary (diesel engine). Kershman et al. [32] investigated a seawater reverse osmosis (SWRO) powered from renewable energy sources (hybrid PV/wind/grid/RO) for small-scale desalination in Libya (300 m^3/day). While the expected nominal power load for the operation of the RO desalination system is 70 kW (net power after recovery), the solar PV system is designed for 50 kW_{peak} and the wind energy conversion for 200 kW nominal output. The objective of this investigation was a reduction of the non-renewable energy consumption to about 40%.

6. Economic analysis

The economic analysis made in this section is based on the use of the life cycle cost (LCC). The life cycle cost is an economic assessment of the cost for a number of alternatives by taking into account all significant costs over the lifetime of each alternative, adding each option's costs for every year and discounting them back to a common base. These costs can be categorized into two types

(i) recurring cost (operation cost and maintenance cost)
(ii) non-recurring cost (batteries and replacement cost) [1,2]:

Cost analysis of autonomous desalination systems usually aims to estimate the cost of a liter or a cubic meter of fresh water, and calculates the contribution of each cost item to the total cost. This identifies immediately the most significant cost items and attracts the attention to what should be examined for possible improvement and cost reduction. In general, cost factors associated with implementing desalination plants are site specific and depend on several variables. The major cost variables are:

(i) quality of feed water where the low TDS concentration in feed water (e.g. brackish water) requires less energy for treatment compared to high TDS feed water (seawater).
(ii) Plant capacity where it affects the size of treatment units, pumping, water tank, and water distribution system. Large capacity plants require high initial capital investment compared to low capacity plants. But due to the economy of scale, the unit production cost for large capacity plants can be lower [1,2].
(iii) Site characteristics where it can affect water production cost such as availability of land and land condition, the proximity of plant location to water source and concentrate discharge point is another factor. Pumping cost and costs of pipe installation will be substantially reduced if the plant is located near the water source and if the plants concentrate is discharged to a nearby water body.
(iv) Costs associated with water intake, pretreatment, and concentrate disposal can be substantially reduced if the plant is an expansion of an existing water treatment plant as compared to constructing a new plant.

Table 10
Percent distribution of cost factors [1].

Cost name	Brackish water (%)	Seawater (%)
Fixed costs	54	37
Electric power	11	44
Labor	9	4
Membrane replacement	7	5
Maintenance and parts	9	7
Chemicals	10	3

(v) Regulatory requirements which associated with meeting local/state permits and regulatory requirements [2].

It is difficult to compare the costs of desalination installations at an aggregated level because the actual costs depend on a range of variables specific to each site [1].

Desalination plant implementation costs can be categorized as: construction costs (starting costs) and operation and maintenance (O&M) costs. Construction costs include direct and indirect capital costs. The direct cost includes land, production wells, surface water intake structure, process equipment, auxiliary equipment, buildings and concentrate disposal (type of desalination technology, plant capacity, large location and environmental regulations). The indirect capital cost is usually estimated as percentages of the total direct capital cost. Indirect costs may include freight and insurance, construction overhead, owner's costs, and contingency costs. The operating and maintenance (O&M) costs consist of fixed costs and variable costs. Fixed costs include insurance and amortization costs. Usually, insurance cost is estimated as 0.5% of the total capital cost. Typically, an amortization rate in the range of 5–10% is used. Variable costs include the cost of labor, energy, chemicals, and maintenance. For low TDS brackish water, the replacement rate is about 5% per year. For high TDS seawater, the replacement could be as high as 20%. The cost for maintenance and spare parts is typically less than 2% of the total capital cost on an annual basis [1].

Table 10 shows the percent cost of various factors for desalination of brackish water and seawater in RO plants. These data are reported in the Sandia National Laboratories report. It can be observed from these data, that:

(i) The fixed costs are a major factor for both, brackish water and seawater.
(ii) The major difference in cost between desalination of brackish water and seawater is energy consumption, while the remaining factors are decreased proportionally.
(iii) Costs associated with membrane replacement, maintenance & parts and consumables are relatively small. These costs depend on the status of technology and may be further reduced as technology evolves, but will not have significant impact on the overall cost of desalination.

The cost and energy figures have been estimated by many authors. The summary is given below as reviewed and reported by Eltawil et al. [1]:

1. The solar still distillation system can produce water for \$20/m^3 (1994), while other researcher estimated solar distilled water production costs as low as \$2.4/m^3. Recent improvements in solar distillation technology make it the ideal technology for remote isolated areas with a water demand less than 50 m^3/day. All other technologies are more expensive at this small scale. While other researcher believes that solar stills are the technology of choice for water production needs up to 200 m^3/day.
2. The dominant competing process is RO that has an energy requirement of between 6 and 10 kWh/m^3 of water treated and

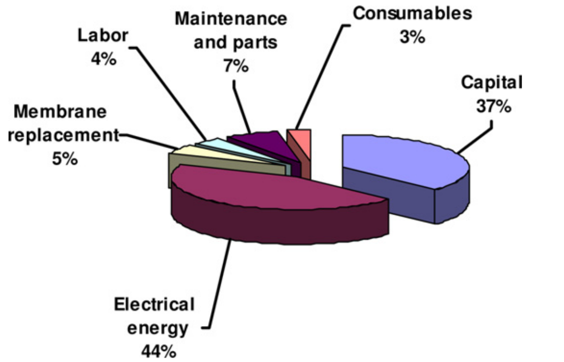


Fig. 26. Typical cost structure for RO desalination of seawater [1].

investment costs of between US$600 and US$2000/m^3 of production capacity [2].

3. The RO technologies with energy recovery systems require the least amount of energy to process seawater (4–6 kWh/m^3) compared to all other technologies. If brackish water is included as a potential input, then the energy requirements for RO drop significantly and are basically equivalent to (0.5–2.5 kWh/m^3).

Using ED treatment for brackish water Comparison of typical costs for seawater desalination by RO and typical thermal processes have shown that for RO, the largest cost reduction potential lies in capital costs and energy costs (Fig. 26). For a typical large-scale thermal desalination plant, energy cost represents 59% of the typical water costs with the other major expense being capital c[illegible] (Fig. 27). It would seem that the most effective cost reduc[illegible] for thermal desalination can be achieved by utilizing alternat[illegible] sources of heat or energy, such as dual purpose plants.

In addition, the development of less costly an[illegible]rrosion-resistant heat transfer surfaces could reduce b[illegible] ca[illegible]l and energy costs [1]. There is more detailed cost co[illegible]risons [illegible]tween the different desalination technologies are give[illegible] Tab[illegible]

The data show that the costs of RO syste[illegible] rang[illegible]m approximately 0.90 cents/gallon (US$2.37/$m^3$) [illegible] a plant w[illegible]apacity of 0.03 million gallons per day to 0.21 [illegible]allon (US$0[illegible]$m^3$) for a 30 million gallons/day capacity [illegible]em.

RO remains the cheaper opt[illegible]n at both lo[illegible]d high production capacities in comparison to [illegible] other technolo[illegible] However, it is important to restate that [illegible]salinat[illegible]n cost data [illegible] extremely site specific, so the compari[illegible]f cos[illegible]cross the different technologies is not as straight forward [illegible]ay appe[illegible]in the presented data. Solar thermal po[illegible]lants [illegible] acqu[illegible] a considerable share on clean electricit[illegible]ene[illegible]on in t[illegible]entury. They are one of the best-suited [illegible]nolog[illegible] to achieve [illegible]e global goals of CO_2 emission reduction. [illegible]ener[illegible]time of a solar thermal power plant is in the order of 0.5 years, while the economic lifetime is at least 25 years [2].

Life cycle emissions of greenhouse gases amount to 0.010–0.015 kg/kWh, which is very low in comparison to those of gas fired combined cycles (0.500 kg/kWh) or steam/coal power plants (0.900 kg/kWh).

Table 11
Unit product costs for conventional and novel desalination processes by capacity [1].

System, type	Capacity millions gallons/day	Unit product cost $Cent/gallon
I-Novel processes		
MEE-VS, 30 effects, aluminum alloy, fluted tubes	90.53	0.182
MEE-ABS, absorption heat pump and gas turbine	2.5	0.133
II-Mechanical vapor compression (MVC)	0.03	1.894
	0.13	1.22
	1.06	0.939
	1.2	0.92
	5.28	[illegible]
III-Reverse osmosis		
Single stage	5.28	[illegible]
Two stage	5.28	0.288
	[illegible]	[illegible]
	[illegible]	[illegible]
	[illegible]	[illegible]
	9.99	[illegible]
	[illegible]	0.314
	[illegible]	0.258
	[illegible]	0.208
IV-Multistage flas[illegible]lination (MSF)		
Dual purpos[illegible]	7.13	0.292
Single purpo[illegible]	7.13	0.621
Gas turbine, waste-heat [illegible]	8.45	0.545
	7.13	0.595
	9.99	0.473
V-[illegible]tiple-effect evaporation (MEE)		
[illegible]l-purpose	6	0.33
[illegible]e purpose	6	0.739
	6	0.529
	6	0.47
	9.99	0.409
[illegible]s turbine, waste-heat	9.99	0.496
[illegible]-ME[illegible]VC		
Single purpose	5.85	0.886
Dual-purpose	5.85	0.496
	5.85	0.587

7. Decision support tool (DST)

To aid the process of cost calculation for a specific desalination technology, a decision support tool (DST) software is used for cost estimation during any project. For analysis, the DST authors [1] suggested to divide the cost of ADS into following categories as follows (Fig. 28):

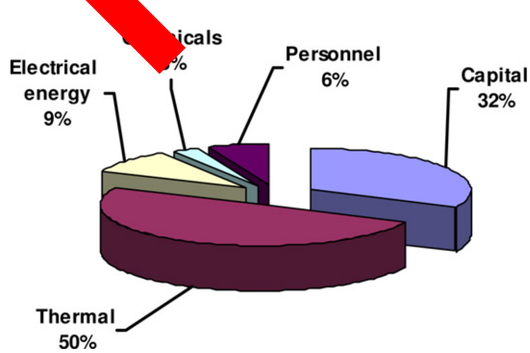


Fig. 27. Typical cost structure for large thermal desalination of seawater [1].

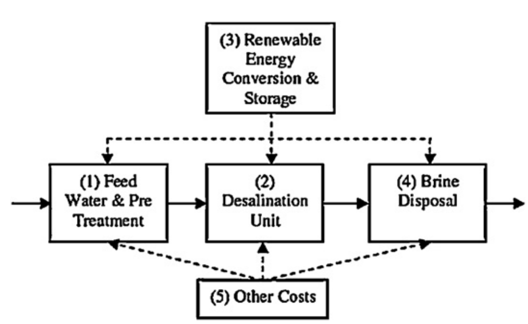


Fig. 28. DST cost categories [1].

i. Cost of feed water system and pre-treatment, including all necessary investment and related expenses required for the supply of brackish or seawater to the desalination main system.
ii. Cost of desalination unit itself.
iii. Cost of supporting source (RES), supplying all the energy needs for the desalination unit, feed water pumps and brine disposal.
iv. Cost of brine water disposal, which could be anything from minimal to very expensive depending upon specific conditions.
v. Other costs. Most of the above categories have (a) an investment and (b) a running cost. The investment cot reflects the annual cost of purchasing and installing equipment or other fixed asset, while the running cost relates to annual expenses and the cost of various consumables which are necessary. The cost per liter or m^3 of fresh water is estimated by dividing the sum total annualized investment plus running costs of all categories by the volume of fresh water produced.

It should be noted, that for a given ADS technology, cost analysis is a site-specific and usually cannot be generalized for applications in other situations. As a general rule, the cost of the produced water by ADS is normally higher than conventional desalination technologies driven by network electricity or conventional fuel thermal energy. However, in the remote areas far from electricity, fuel and fresh water resources as well as areas where the economic driven is tourism, the water price is acceptable. The developments currently underway suggest that ADS applications are going to become more wide spread.

An effective integration of desalination and renewable energy technologies will allow countries to address water shortage problems with a domestic energy source that does not produce air pollution or contribute to the global problem of climate [illegible]. Meanwhile the costs of desalination and renewable energy systems are steadily decreasing, while fuel prices are rising and fuel supplies are decreasing. Finally, the desalination units powered [illegible] renewable energy systems are uniquely suited [illegible] de water and electricity in remote areas where water [illegible] electricity infrastructure is currently lacking.

8. Conclusion

The use of renewable energies for desalination appears nowadays as a reasonable and technically attractive option toward the emerging and stressing energy and water problems.

For low-density population [illegible] as worldwide there are lack of fresh water as well [illegible] power grid connections. Therefore, the cheap fresh water may be produced from brackish, sea and oceans [illegible] using wind turbines, solar panels and other emerging renewable energy technologies.

The connection of photovoltaic cells to membrane processes in desalination is [illegible] alternative for stand-alone desalination systems in remote areas. Nevertheless, if wind power is available, it exhibits lower energy cost than solar PV energy. For brackish water desalination, both of RO and ED powered by wind turbines are usually the best selection. Nevertheless, solar distillation may be advantageous for seawater desalination, although other renewable energy resources have to be taken into account.

Geothermal energy is suitable for different desalination process at reasonable cost wherever a proper geothermal source is available because there is no energy storage is required. Moreover, other systems require further analysis for evaluating their potentials of development, applications and performance.

The most attractive technologies of renewable energy application in desalination are wind and PV-driven membrane processes and direct and indirect solar distillation. Nevertheless, the coupling of renewable energy and desalination systems has to be optimized. Also, the new pretreatments may improve the performance by permitting a considerable increase of the operating temperature in distillation plants.

Environmental issues are associated with brine concentrate disposal, energy consumption and associated greenhouse gas production. On the other hand, social issues may include the public acceptance of using recycled water for domestic dual-pipe systems, industrial and agricultural purposes.

Appendix A. Glossary

Brackish: Water that typically con[illegible] than 10,000 ppm salt-more salt than freshwater but l[illegible] than th[illegible] n seawater.

Brine: Water that contains greater than 50,000 ppm salt. Brine discharges from desalination plants [illegible] also include constituents used in pretreatment process. See also "Concentrate".

Cogeneration: A power plant that is designed to conserve energy by using "waste heat" from generating electricity for another purpose, for example to thermal desalination or to warm SWRO feed water.

Concentrate: Water containing concentrated salts rejected by the membrane. See also "Brine".

Deaeration: Removal of oxygen. A pretreatment process in desalination plants to reduce corrosion and fouling.

Dissolved air flotation (DAF): A pretreatment process in desalination plants to remove solids and organics.

Distillation: A process of desalination where the water is heated to produce steam. The steam is then condensed to produce product water with low salt concentration.

Electrodialysis: Most impurities in water are present in an ionized (electrically charged) state. When an electric current is applied, the impurities migrate toward the positive and negative electrodes. The intermediate area becomes depleted of impurities and discharges a purified stream of product water. This technology is used primarily for brackish waters.

Feedwater: Water fed to the desalination equipment. This can be source water with or without pretreatment.

Fouling: Contamination or biological growth on the reverse osmosis membranes or pretreatment filters.

Freshwater: Water that contains less than 1000 milligrams per liter (mg/L) of dissolved solids; generally, more than 500 mg/L of dissolved solids is undesirable for drinking and many industrial uses.

High-pressure differential pressure (HP DP): The pressure at the high-pressure inlet port of the PX device minus the pressure at the high-pressure outlet port of the PX device.

Infiltration gallery: A method used for the area where seawater enters the SWRD process. Perforated pipes are arranged in a radial pattern in the sand onshore below the water level. Water in the saturated sand enters the perforated pipes.

Ion exchange: A reversible water treatment process. A charged polymer exchanges Na^+, H^+, Cl^-, or OH^- for other ions in a solution.

Multiple effect distillation (MED): A form of distillation. Evaporators are placed in series, and vapor from one effect is used to evaporate water in the next lower pressure effect. There are several forms of this technology, one of the most common is the vertical tube evaporator (VTE).

Multistage flash (MSF): A form of distillation. Intake water is heated then discharged into a chamber maintained slightly below the saturation vapor pressure of the incoming water, so that a fraction of the water content flashes into steam. The steam condenses on the exterior surface of heat transfer tubing and becomes product water. The unflashed brine enters another chamber at a lower pressure, where a portion flashes to steam. Each evaporation and condensation chamber is called a stage.

Nanofiltration (NF): A lower pressure membrane filtration technology sometimes used for pretreating reverse osmosis feed-water.

Permeate: Water purified by a reverse osmosis membrane.

Product water: The desalted, post-treated water (or permeate) delivered to the water distribution system.

Recovery: Ratio of permeate to membrane feed flows, typically expressed as a percentage.

Reverse osmosis (RO): A process where pressure is applied continuously to feedwater, forcing water molecules through a semi-permeable membrane. Water that passes through the membrane leaves the unit as permeate or product water; most of the dissolved impurities remain behind and are discharged in a concentrated brine or waste stream.

Salinity increase: The increase in the salinity of the membrane feed stream caused by the energy recovery device. Salinity increase varies with the membrane recovery rate. It is typically expressed as a percentage increase of the membrane inlet stream above the salinity of the system feed-water according to the following equation:

$$\text{Salinity increase} = \frac{\text{membrane inlet salinity} - \text{system feed} - \text{water salinity}}{\text{system feed} - \text{water salinity}} \times 100\%$$

Seawater reverse osmosis (SWRO): Reverse osmosis desalination of seawater.

Scaling: Salt deposits on the surfaces of a membrane.

Total dissolved solids (TDS): Total salt and calcium carbonate concentration in a sample of water.

Vacuum freezing (VF): A process of desalination where the temperature and pressure of the seawater is lowered so that the p[illegible] water forms ice crystals. The ice is then washed and melted to p[illegible]duce the product water. This technology is still being develope[illegible] and is not commercially viable.

Vapor compression (VC): A form of distillation [illegible]tion of feed-water is evaporated, and the vapor is sent [illegible] co[illegible]essor. Mechanical or thermal energy is used to compr[illegible]he vap[illegible] which increases its temperature. The vapor is th[illegible] product water and the released heat is u[illegible]o eva[illegible]e the feed-water.

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